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<u>EAVE WEST</u>

Stan Watson
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EAVE WEST was designed for use as a testbed to investigate various component technological concepts. The goal is not to derive an optimal vehicle system, but to combine different technologies and observe their relationship to one another. Presently the effort is to determine various areas of artificial intelligence that might be adaptable to upgrade state-of-the-art vehicle technology. An LSI 11/23 has been incorporated into the vehicle for these and other experiments. A fiber optics communication link will be installed on the vehicle. It is a full duplex communication link that will be freely deployed from the vehicle with a pre-twist in an attempt to eliminate the entanglement problem. The 1200 baud serial digital data will be multiplexed on the retrace scan of the uplink TV signal. A dichroic duplexer will be used to transmit down over the same fiber.

A second area being investigated is a magnetic pipeline follower. The receiver is finished and is working in the laboratory. The next step is to install both the fiber optics and magnetic pipeline follower in the vehicle for an open ocean test sometime this calendar year.

(A detailed description of the EAVE WEST vehicle can be found in Heckman, P. J. 1980. Free-Swimming Submersible Testbed (EAVE WEST). Naval Ocean Systems Center TR 622, San Diego, October 1980.)

Research in Supervisory Control of Underwater Systems at MIT Man-Machine Systems Laboratory

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Massachusetts Institute of Technology
Cambridge, Massachusetts

The work being conducted at this laboratory that is related to the subject of this workshop is sponsored by the Office of Naval Research and by MIT Sea Grant. ONR's interest is in the experimental man-machine aspects of supervisory, control while Sea Grant is more interested in hardware demonstration.

Real-Time Vehicle Simulation and Control

Kazerooni has developed a non-linear, general vehicle model that runs in real-time in conjunction with a computographic display. (See Kazerooni, H. 1981. General Purpose Digital Simulation of Underwater Vehicles. Proc. IEEE Conf., Oceans '81, v. 1, pp. 123-126.) Several different vehicles have been simulated on this system, including the RCV-225 and the manned vehicle ALVIN. Vaaler of MIT is discussing with the ALVIN group the possibility of including automatic control features on ALVIN.

Other simulation activities include a project for control of systems evaluation and design, such as that discussed above involving ALVIN. This activity includes servo level control as well as bottom-following algorithms incorporating relatively simple sonar systems. Another program employs an electromechanical simulator to interact with real-time, human operator experiments. This is an actual vehicle that can be maneuvered about on the seafloor and is equipped with a TV camera. Its purpose is to make the TV camera move with the dynamics produced by the model. This allows simulation of a variety of vehicles and attains a reasonably relevant video picture similar to what

<u>AUSS (Advanced Unmanned Search System)</u>

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The AUSS program has been conducted along four major task elements:

<u>Analysis</u> -- To determine the optimal means of conducting deep ocean search.

<u>Testbed</u> -- The vehicle will be used to verify the deep ocean search technologies that the analysis indicated were lacking.

<u>Component and Subsystem I&E</u> -- Identify components, particularly the acoustic link with the vehicle, that need to be developed, including pressure hull technologies (graphite/expoxy).

<u>Acquisition Data Package</u> -- Will consist of a package that will be presented to various search activities to assist them in selecting the optimal data-gathering instrumentation for their purposes

The AUSS vehicle is designed to search for objects between 2,000 and 20,000 feet depths, and will be deployed from a surface support platform. It is launched negatively buoyant and sinks to the bottom where it assumes a horizontal position just above the seafloor. Upon acoustic command from the surface, it releases its tether and becomes operational. In the search mode, a scanning sonar is used to locate objects, and, upon command from the surface, it will home on an object of interest to deploy the video camera. All sensor data are acoustically sent to the surface for analysis.

Vehicle power is provided by silver zinc batteries. Doppler sonar is used for dead reckoning navigation. Two stern propellers provide lateral and horizontal thrust, and two vertical thrusters provide heave motion. A Honeywell acoustic navigation (transponder) system is also provided. The scanning sonar is a modified Edo sonar. Total vehicle length is 14 ft, its diameter is 30 inches, and it displaces 2000 lbs.

The desired acoustic link charateristics are:

Operating depth	2,000-20,000 ft
Surface platform	
Horizontal offsets	0-45°
Up-data rated	4800 bits/sec
sonar	
TV	
status (vehicle)	
Down-data rate	1200 bits/sec
supervisory commands	
Maximum bit error rate	1×10^{-5} bits/sec
Frequencies occupied	8kHz - 14kHz

In June of 1981 an acoustic transmission package was tested in 15,000-foot water depth using 15 watts of power on 2 independent sidebands of an 11 kHz carrier. This test demonstrated that:

1. low resolution SSTV (slowscan TV) pictures can be transmitted with offsets of 0-54°;
2. 4800 bits/sec (2400 bits/sec per sideband) digital data were transmitted (10×10^6 bits with offsets of 0-45°) with a bit error rate of 1×10^{-6};
3. 2.6×10^6 bits of 1200 bits/sec digital data were transmitted down to the test package (simulating vehicle commands) with 0 errors for offsets of 0-54°;
4. The data gathered indicate that operation to 20,000-foot depths is possible by doubling the power.

Accomplishments to Date and Future Plans

A. Hull Structure

completed: graphite cylinder design
titanium end bell design
graphite cylinder in fabrication (2 in. wall thickness)

FY 81 Plans: take delivery on graphite cylinder
take delivery on end bell castings

B. Scanning Sonar

completed: preliminary at-sea evaluation of scanning sonar placed contract for Edo model OAS-4059 sonar (2^{o} resolution, 400 m maximum angle, 1000 elements/scan)

FY 81 Plans: Take delivery of sonar

C. Shipboard Vehicle Navigation Subsystem

completed: procured Honeywell RS-900 (short baseline) system.
designed and fabricated ship interface equipment

FY 81 Plans: Sea tests in conjunction with BUMP (Benthic Untethered Multipurpose Package) system to study compatibility with acoustic link.
Incorporate independent navigation DOT (Deep Ocean Transponder) into testbed system.

D. Test-Bed System Mechanics

completed: static weight/buoyancy stability computer program with compensation for pressure and temperature.
Sizing, selection, and preliminary design of propulsion motors, including contract for magnetic couplings.
Battery cost/efficiencytradeoff study; selection of 20 KW-HR silver zinc.
Designed and developed prototype of weight dropper.

Established preliminary testbed vehicle configuration.

FY 81 Plans: Refine design of testbed structure, components, and interfaces to graphite pressure housing. Fabricate and test thruster motors.

E. Subsea Navigation Subsystem

completed: RUWS straza doppler system procurement and sea trials.

FY 81 Plans: Complete breadboard testbed doppler subsystem and perform in-water tests.

F. Vehicle Control-Obstacle Avoidance Subsystem

completed: Analysis of stopping dynamics for free-swimming vehicle.
Negotiated contract for forward or bottom obstacle detection capability on Edo search sonar.

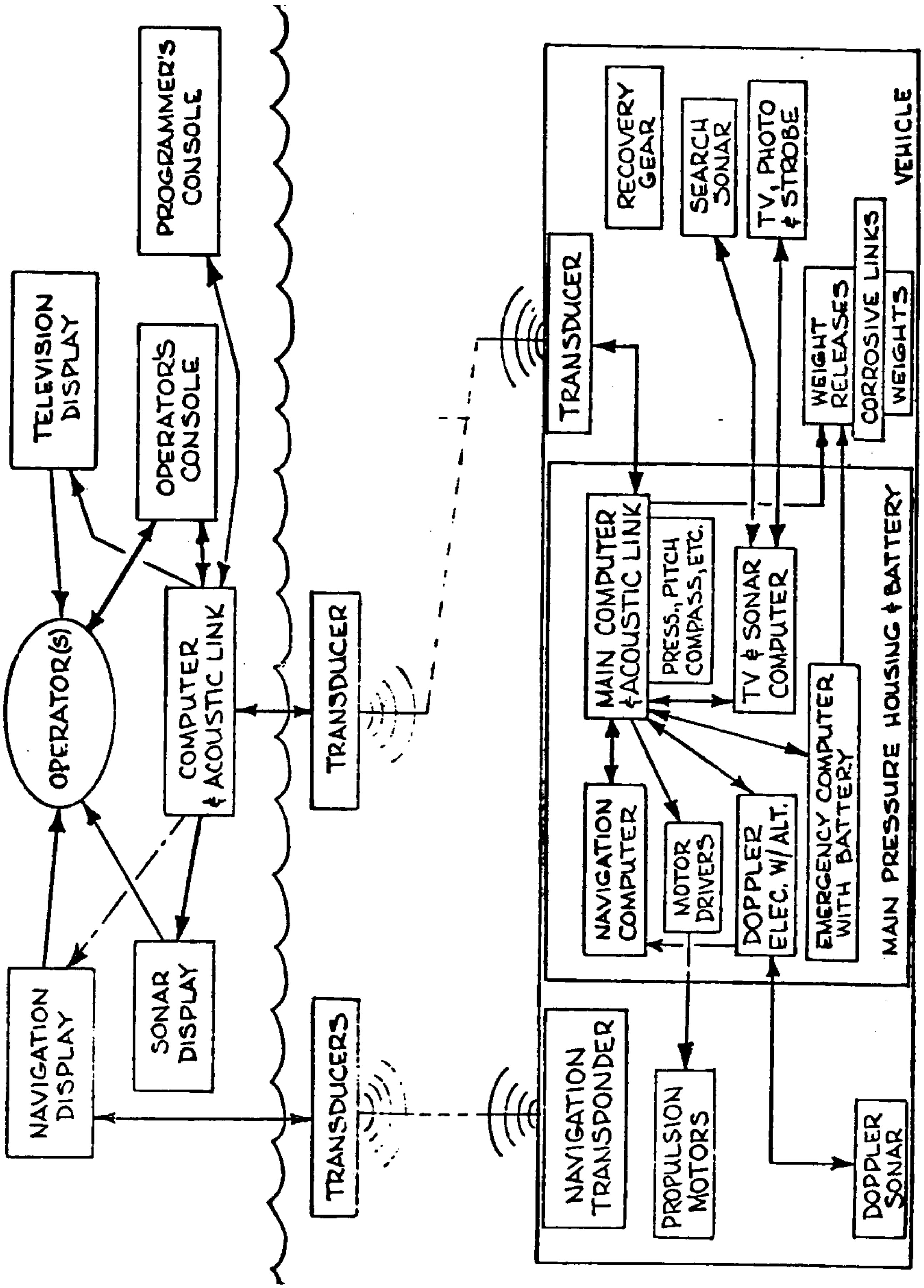
G. Testbed System Software

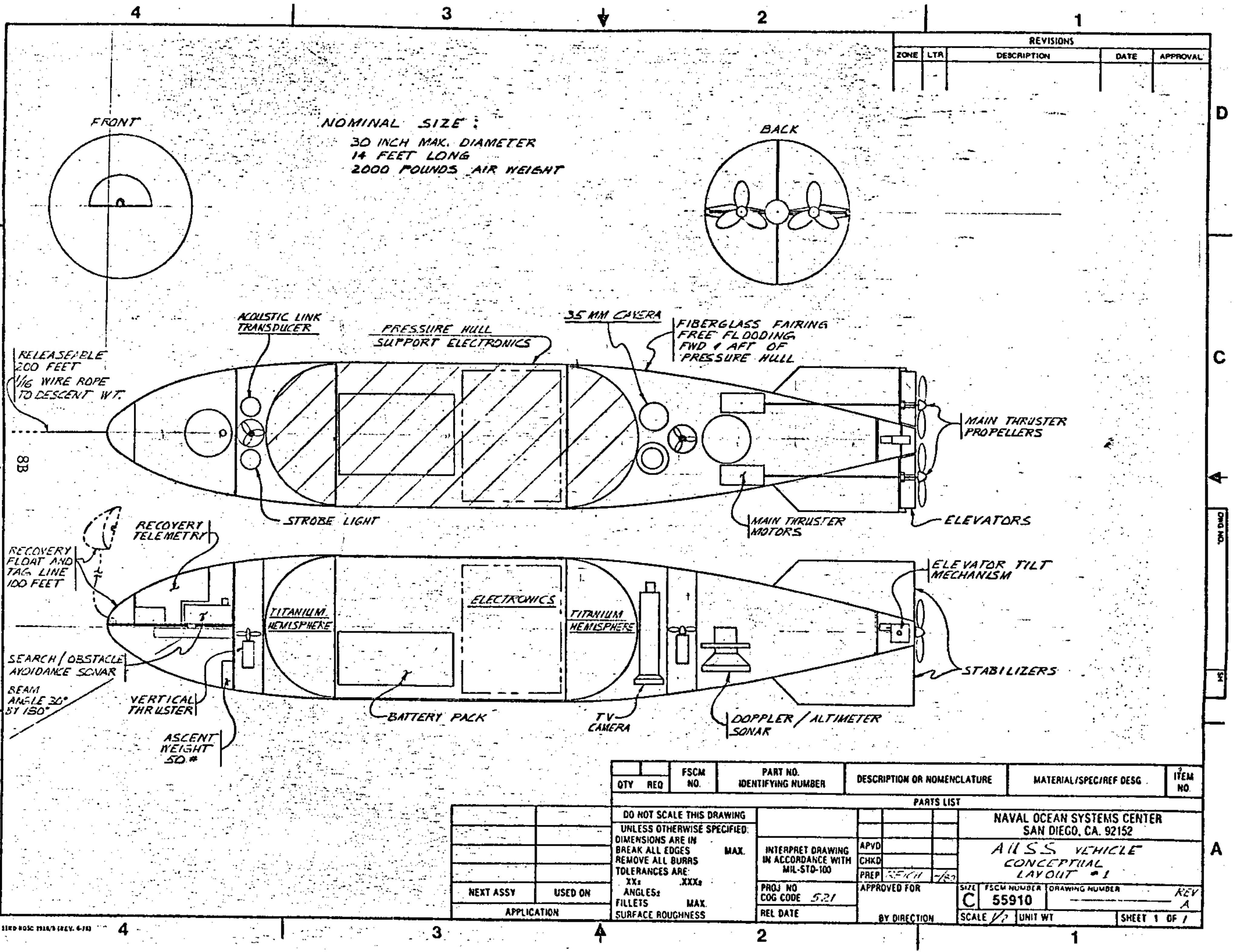
completed: Defined testbed system scenario.
Established subsea computer system architecture.
Procured subsea computers and executive programs.
Defined operator command structure.
Generated system variable names list.
Started computer program flow charts for subsea computers.

FY 81 Plans: Establish software quality control guidelines.
Write software code for vehicle control loops (NRL).
Begin compiling program for subsea computers.

The first sea tests and shakedown of the AUSS are presently scheduled for November 1983.

AUSS - MAJOR SYSTEM COMPONENTS




FRONT
NOMINAL SIZE:
30 INCH MAX. DIAMETER
14 FEET LONG
2000 POUNDS AIR WEIGHT
BACK
RELEASEABLE 200 FEET 1/16 WIRE ROPE TO DESCENT WT.
ACOUSTIC LINK TRANSDUCER
PRESSURE HULL
SUPPORT ELECTRONICS
35 MM CAMERA
FIBERGLASS FAIRING FREE FLOODING FWD & AFT OF PRESSURE HULL
MAIN THRUSTER PROPELLERS
STROBE LIGHT
MAIN THRUSTER MOTORS
ELEVATORS
RECOVERY TELEMETRY
RECOVERY FLOAT AND TAG LINE 100 FEET
TITANIUM HEMISPHERE
ELECTRONICS
TITANIUM HEMISPHERE
ELEVATOR TILT MECHANISM
SEARCH / OBSTACLE AVOIDANCE SONAR
BEAM ANGLE 30° BY 180°
VERTICAL THRUSTER
ASCENT WEIGHT 50 #
BATTERY PACK
TV CAMERA
DOPPLER / ALTIMETER SONAR
STABILIZERS
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Offshore Oil and Gas Operations of ROVs

Drew Michel
Taylor Diving and Salvage Co., Inc.
Belle Chasse, Louisiana

There are at present some 4000 offshore platforms world-wide and several thousand miles of undersea pipeline. The oldest platform was installed in 1947, and divers have been employed until recently to do all of the underwater work required. Divers have been used because the work has been simple in nature (e.g., rigging, cutting) and did not require the use of sophisticated devices to be accomplished. Divers have dominated this market only because they could do the job better or more quickly than a computing system and at a profit to the offshore operator. The only reason Remotely-Operated Vehicles (ROVs) have begun to replace the diver in the past five years is because they could meet the basic criterion: profit. In the oil industry, if your vehicle or device is not profitable to the operator, he will not use it. The offshore drilling and production community is not a research and development operation.

As an example, the lowest cost for a diving spread is approximately $500/day. The average cost for a ROV spread is $3,500/day, and the average cost for a pipe-laying barge spread is $100,000/day. If the ROV can reduce by three or four days the time required for the barge, then its cost is acceptable.

Taylor Diving has eleven ROVs. These consist of eight RCV-225s, one SCORPIO, one RCV-150, and a vehicle we have devloped in-house. These vehicles are working in the North Sea, Southeast Asia, the Mediterranean, and offshore Brazil.

One job we completed on the trans-Mediterranean pipeline in 1979 serves as an example of the type of performance requirements I described earlier. At a depth of 1,770 feet, rock outcrops were encountered that had to be removed. A manned vehicle had been trying for one year previous to our entry to place explosive charges on these outcrops. At best, it could only place two sets of charges per day, and the contractor had decided to give up on this approach. We designed an approach that consisted of a 7-ton frame that held 24 charges. The frame was lowered to just off the bottom. There, an RCV-225 maneuvered it into position, then actuated a hydraulic release that permitted the charges to fall to the bottom where they were subsequently detonated. We were able to plant and fire five thousand of these charges over the next year (up to as many as eleven sets of twenty four each in one day) and complete the work as required.

Present and Future ROV Applications

We are involved in several areas that will employ improved ROVs in the immediate future. Following are brief descriptions of these efforts.

Platform Inspection: Taylor Diving is developing an ROV for this purpose. Its mission will consist of "flying" to a preselected area on the structure, then cleaning (to bare metal) the area of interest, videotaping and/or taking color stereophotographs, and, lastly, performing some form of ultrasonic or magnetic particle inspection. Although divers can now perform this job, we believe that in depths greater than 300 feet the ROV will be more economical.

__Pipeline Inspection__: Some pipelines, particularly in shallow waters, are completely buried, others only partially so, and others, in deep water, not at all. A major concern of the production companies is the presence of sections that are damaged or suspended because of current erosion or outcrops. We envision using a device such as a proton magnetometer to track the pipeline from the ROV. When the pipe becomes visible, we will take videotapes or photographs of it. If it remains buried, the assumption is that there is no damage. One operator is pursuing this program in offshore Australia where a dynamically positioned (DP) ship is acting as the support ship for the ROV. The ship remains in position over the ROV by using a Honeywell tracking system. At present there is an arrangement (via a computer) whereby the ship follows the vehicle automatically. In essence, the vehicle operator steers the ship. Later we are aiming at letting the gradiometer signals steer the vehicle and the ship also. The result we are trying to achieve is a totally automatic pipeline inspection, all controlled by a computer.

__Platform Salvage__: Hundreds of platforms in the Gulf of Mexico have outlived their usefulness and must be removed. Although divers can work as deep as many of these platforms are located, we see the application of ROVs at depths below 300 feet. At present we are working with Exxon Production Research to develop a technique that will enable an ROV to place shape charges on the platform legs, and, once all the legs have shape charges attached, a slice of the platform will be cut off by detonation. A requirment of this project is that all legs must be cut at one time. So far, we have demonstrated the capability of cutting through a five-foot diameter steel leg.

Concerning autonomous vehicles, oil companies and service companies such as ours will not enter this field or fund this work until we see something that can do the job better than it is presently done. This is not to say that we are uninterested in what is being developed. But, we will not fund research and development until there is a definite, foreseeable payoff in the undersea oil and gas community.

Question Period

Question: What is the biggest problem with ROVs?

Answer: Cable entanglement on structures, particularly entanglement on cathodic protection anodes and in discarded lines, such as monofilament fishing lines, which festoon many structures.

Question: Did you have any entanglement problems in the Mediterranean pipeline operations?

Answer: No. I believe the reason for this is because the vehicle works out of a deployment cage and, consequently, the cable is held taut. This greatly reduces the entanglement potential that one would encounter without the deployment cage.

Question: Do present vehicles, in particular the RCV-225, have adequate propulsive power?

Answer: The RCV-225 has 1/10 hp thrusters; this is inadequate. We would like to have greater power and a more rugged umbilical cable and reduced vehicle costs. The vehicle we are developing is in response to some of these shortcomings. Our philosophy is that the vehicle itself should be the least expensive part of the system. By putting the absolute minimum of components on the vehicle and keeping the majority of components on the surface, we believe that we can reach this goal.

<u>Question:</u> Is the TV you are using adequate?

<u>Answer:</u> Color TV is woefully inadequate. Too much light is required, there is too much blooming, and too much color intonation. We use it, but only because the client expresses it as a requirement.

<u>Question:</u> From what you have shown us, it seems as if ROVs can equal the performance of manned submersibles. If this is correct, then what accounts for the growth of manned vehicles (such as Atmospheric Diving Suits, Observation/Work Bells and one-man vehicles) in the area of drilling support?

<u>Answer:</u> It's simply a matter of breaking through tradition. Offshore operators are reluctant to substitute a new device for one that has been performing adequately. We encountered this sort of opposition initially, some four to five years ago, but once we demonstrated our performance, acceptance came along accordingly.

Control System Test Vehicle (CSTV)
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Naval Coastal Systems Center
Panama City, Florida

The Control System Test Vehicle (CSTV) is an autonomous 30-foot underwater vehicle designed for hydrodynamic research. The vehicle weighs about 9,000 pounds and is driven by a 25-horsepower electric motor. The onboard instrumentation and motor are powered by silver zinc batteries that give the CSTV a nominal endurance of four hours. The CSTV was built under the Naval Sea Systems Command Advanced Submarine Program and is currently based at the Naval Coastal Systems Center, which is responsible for sea test operations; navigation/guidance/control hardware and software; and maintenance. The vehicle contains (1) highly accurate instrumentation for measuring the dynamic motion of the vehicle; (2) a magnetic tape system to record the measured data; (3) a low data rate digital acoustic position and telemetry system (APATS) to start the vehicle, monitor its status, override the onboard computer, and provide a range measurement used in the determination of navigational position; and (4) a militarized computer to collect data, perform navigation, guidance and control, and protect the vehicle.

The CSTV has been designed to perform sea tests of four-hour duration in the open sea during which it performs preprogrammed maneuvers to excite hydrodynamic phenomena. These data are recorded for subsequent analysis by hydrodynamicists and engineers on large main frame computers. The sensitivity requirements of the analysis methods demanded precision fabrication of the vehicle and highly accurate motion sensors.

Some of the measurement instrumentation includes:

(1) speed sensor for longitudinal axis water relative velocity;

(2) pitot tube for 3-axis water relative velocity;

(3) strain gauges for force and moments on selected appendages;

(4) accurate measurements of angular position of eight control surfaces;

(5) advanced inertial navigation system;

(6) three depth gauges.

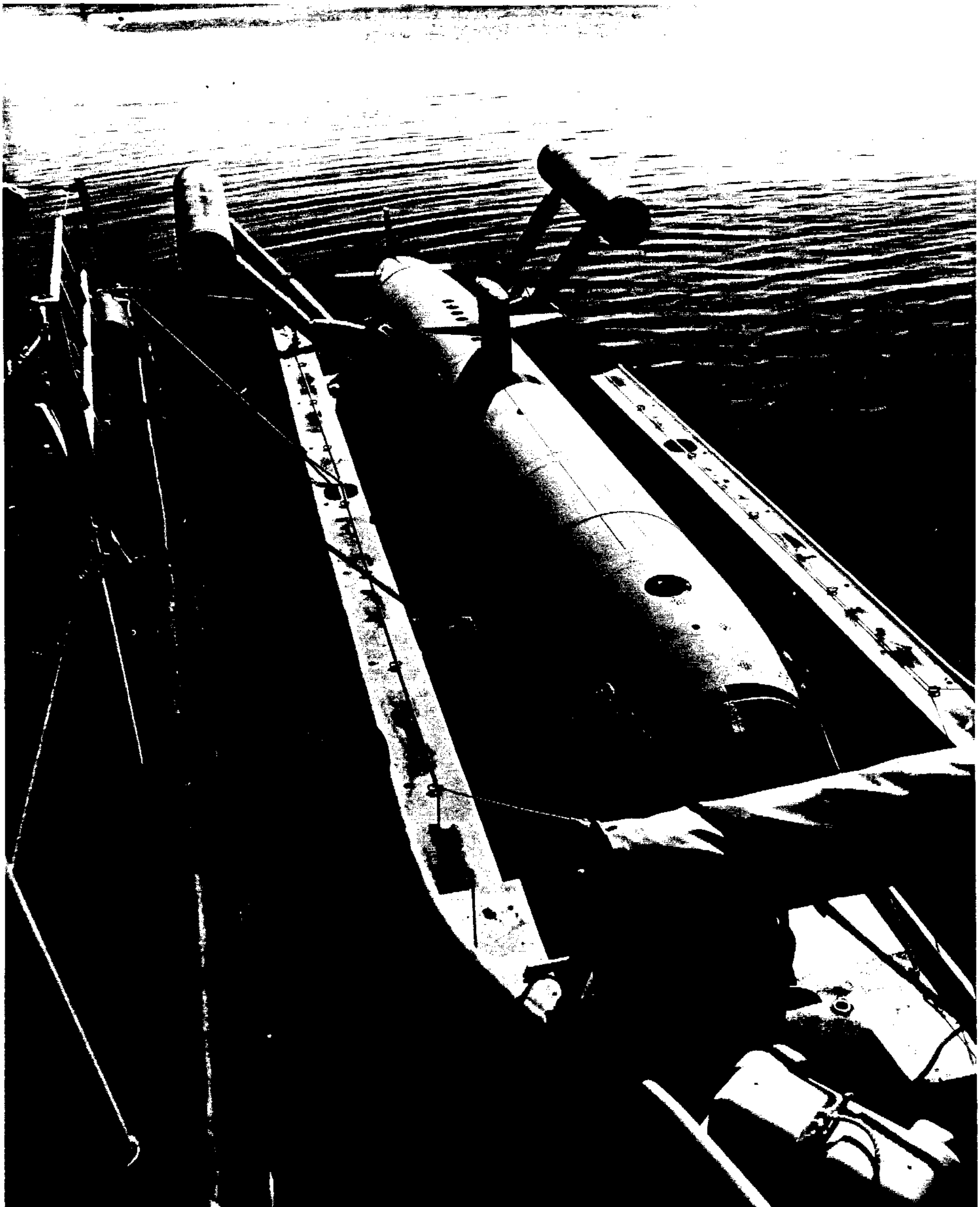
Operational requirements dictated a need for communications and range measurement for navigation purposes between the CSTV and an anchored tender craft from which the CSTV is launched and about which the CSTV maneuvers. The 8-bit word acoustic transmission link APATS was devised. Two synchronized clocks at the anchored tender craft and CSTV provide range by measuring the time of arrival of an acoustic transmission. Because most sea tests, for a variety of reasons, will be performed near the surface or in relatively shallow water (40-100 feet), the inherent multipath problem resulted in reliable transmission at a relatively low data rate of eight bits in six seconds. This data rate was dictated by the communication scheme used and the wide widths of the acoustic pulses required for reliable detection. The low data rate necessitated an autonomous ability in the vehicle to protect itself during high speed maneuvering.

Except for a few overriding acoustic commands, the onboard computer has complete control of the CSTV. The onboard computer has been preprogrammed to interpret a given 8-bit command to perform preprogrammed maneuver number 6 (which may be a porpoising maneuver at five knots). However, at a 10 Hz rate, the computer, using a hierarchy of logic, checks the status of the vehicle--where it is in its environment--and decides whether to perform the received command. As an illustration, the vehicle might be told to perform a high-speed maneuver for three minutes. After one minute, the vehicle might pass a preprogrammed emergency depth threshold and be in danger of colliding with the bottom. The logic in the computer would terminate the maneuver and initiate an emergency override.

The onboard computer is a Rolm 1664 militarized computer with 64K 16-bit words of memory. It performs the functions of guidance, control, safety, navigation, and data acquisition. High level Rolm FORTRAN computer language and a real-time multitasking, operating system create an ideal environment for programming the complex functions of the CSTV in a simple way, yet still allowing maintenance of speed and flexibility. Thus, the onboard computer can act as a testbed for evaluating new control, safety, and navigation algorithms.

The CSTV can be put into a variety of external geometrical configurations to investigate hydrodynamic performance. The dynamic data collected will later be analyzed to evaluate the different geometrical configuration.

For further information, refer to: Seijd, J., K. Watkinson, and W. Hill. April 1980. "A Submarine Control System Test Vehicle." In Naval Engineers Journal, pp. 148-155.



CSTV Strapped Into Transport Sled. (Photo courtesy of Naval Coastal Systems Center)

<u>Unmanned Free-Swimming Submersible</u> (UFSS)

Earl Carey
U.S. Naval Research Lboratory
Washington, DC

For the benefit of those who did not attend last year's symposium, I will present a brief synopsis of the UFSS vehicle and our research and development efforts during the past twelve months.

The vehicle is the product of a systems study that evaluated emerging technologies in 1975. The goal of the study was to determine if a vehicle with a range of 1,000 nautical miles could be built. The result of this study is a vehicle designed to be laminar over 90% of its body surface. The vehicle characteristics are:

Length: 20 feet

Diameter: 4 feet

Weight: In air, 5,420 pounds (plus 2,600 pounds of entrained water)

The pressure vessel encompasses some 75 $feet^3$ and contains the energy pack; control, navigation and telemetry computers; and the trim and variable ballast system.

Tests were conducted during the summer of 1979 in the seaplane landing area off Solomons Island in the Patuxent River. Approximately three months were spent on these initial sea trials. The peculiar shape of the hull presented considerable handling problems. The design analysis showed that any dents in the hull would degrade the vehicle's low drag characteristics. A dimple in the bow produces a turbulent wake with an arc of about seven degrees that travels the length of the vehicle. Consequently, it is very easy to destroy the low drag characteristics of this vehicle. The orange portion of the vehicle is a fiberglass, rib-stiffened dome; the white portion is an aluminum afterbody. The afterbody consists of two segments: the tail cone, which is milled out to create a skin approximately 1/8 inch thick; and the fins, composed of aluminum-stiffened syntactic foam.

The results of the systems study and the testing are given in the following reports:

1. UFSS System Description
   NRL Memorandum Report 4393
   (access to this report is restricted)
   This report describes all the onboard systems, such as navigation, propulsion, telemetry, energy, and variable ballast and trim systems.

2. The NRL Unmanned Free Swimming Submersible (UFSS)
   NRL report 8459
   (access to this report is restricted)
   This report describes the tradeoff analyses conducted to arrive at the present concept. It also describes some of the test-derived preliminary data analyses.

During the past year the vehicle program was supported with two projects. The first project was a control system study which evaluated the original classical design against a newly designed LQR controller for the vehicle. The second project was an image processing survey and study, intended to evaluate methods of enhancing the vehicle's autonomy.

We now think the UFSS shape might have produced more problems than it solved. Handling it required using a large strongback, and 20-foot cables that were cumbersome. If the vehicle inadvertently touched the bottom and was scratched, its low drag characteristics were destroyed. Regarding its present operating capabilities, it is powered (lead acid batteries because of cost) to go 75 miles. The maximum run to date has been ten minutes at an estimated speed of 3.5 knots, although the design is for 5 knots. The run time was a restriction imposed by the test range not by the energy system.

The original vehicle controller was designed using classical linear feedback techniques. The system equations were developed and a solution found using Laplace transform techniques. The control law algorithms were implemented in a 8080 microprocessor computer. All sensors, except heading, had analog outputs that were fed to an A/D converter for digitalization. The outputs to the control surfaces and the motor speed controller were analog voltages from a D/A converter. The control system study, undertaken later, was an attempt to compare the original controller to a linear quadratic regulator (LQR) controller design using modern control techniques. The results showed no major difference between the classical design and that of the linear quadratic regulator. This result might be owing to the simplistic model data used to develop the controller designs. If more definite data could be obtained we feel that significant differences would become apparent. The results of the study can be summed up as follows:

a. no difference in the directional axis controller;

b. an improvement in the longitudinal axis control response time;

c. the classical design oscillates about the commanded depth; the LQR does not.

It should be recognized that the LQR controller uses all the states and therefore requires more sensors than the classical controller.

The second project worked on this year was a study to evaluate the possibilities of correlating search sensor data to enhance the identification of man-made objects. This study started with a survey of existing search data, such as bottom photographs, sidescan sonar records, and magnetometer data. Two problems were encountered: 1) the available data were not sufficiently annotated to allow for time-correlation, and, 2) analysis showed that the ranges of the sensors made their outputs marginally correlatable.

Acoustic data, however, proved to be more promising in view of the current advances in elastic wave theory, particularly Lamb wave theory, in which major advances have taken place in the past five years. For example, if you target a cylinder and impinge upon it, more information is available in the return than is generally used. The record shows a sudden build-up in intensity, then a blank, then another build-up in intensity. When you take a close look at this data you find there are components that depend on modes of oscillation unique to the geometry of the target, e.g., plate, sphere, or cylinder. We feel this area will give us the most information regarding the identity of man-made objects.

We ran tests in which rocks, metal plates, spheres, and cylinders were insonified. Analysis of the return signals has shown that each has characteristic modes that are excited and propagate energy. These modes can be identified and used to classify objects. There is, for example, an identifiable difference between the acoustic response of a rock and that of a man-made shell.

This study has indicated to us that a facility for investigation of models in a controlled environment would be beneficial at this time. We plan to develop a simulation facility that will allow investigation of objects insonified by various signal formats and types (pulse codes, FM slides, or bionic type signals). Two facilities at NRL could be used for these tests: a 700 gallon pool and a 50 x 50 x 75-foot reactor pool. Although we will look at other sensory data--magnetics and photography, for example--we feel the most promising area is acoustics.

EAVE EAST

Dick Blidberg
Marine Systems Engineering Laboratory
University of New Hampshire

The EAVE EAST vehicle is designed to perform tasks characterized by a requirement for a high degree of maneuverability in a confined work area.

The function of the program is to develop technology related to the evolution of autonomous vehicle systems. Since 1977 three essential tasks have been assigned. They are:

1) pipeline inspection;
2) structural inspection;
3) under-ice data collection.

In each task, the objective is to examine system technology and to perform demonstration experiments.

Program Development

1977-1979: The development task was to design a vehicle-based sensor system capable of detecting an exposed pipeline, and to so control the vehicle that it may acquire and follow the pipeline. A simple computer system was constructed to accept the inputs of twelve acoustic ranging sensors and to employ them in a coarse pattern recognition system to generate steering information and altitude.

Emphasis was also placed on the navigation system alternatives. We defined five navigation systems as pertinent to our program: 1) dead reckoning (compass, preprogrammed maneuvers); 2) homing (i.e., phase-arrival navigation system); 3) passive navigation system (range measurements using synchronous clocks and timed acoustic pulses); 4) transponder navigation system (relative positioning, 100-130 KHz); and 5) a transponder/intertial navigation system (accelerometers, rate gyro, for example).

Development attention has been placed principally on the first four systems. In 1979 the EAVE EAST vehicle successfully acquired and followed a bottom pipeline.

1979-1982: The system, called Structural Inspection Mission System (SIMS), has evolved into a three-year task. The vehicle, essentially identical to EAVE EAST, has been given the task of examining a specified underwater structure. Placed in the water up to 300 feet away, it homes in on a structure-mounted transducer until the range is approximately 140 feet. A three-transponder navigation system in the region near the structure, plus a pressure gauge, permit obtaining a high precision x, y, z position fix. The vehicle is then to penetrate within the structure, to transit through it to a "work station" where it performs the simple task of photographing a target. It then retraces its path through the three-dimensional maze, to return to its launching position.

To accomplish the above mission it was necessary to develop a high-resolution acoustic navigation system. To do this, we had to define the mission in the computer's terms. Because of the complexity, we had to develop a program on a large computer to explore program alternatives. The computer's task was to examine the structure and then define safe passage areas within. Although we started with a very simple structure (i.e., a cube), the methods developed could be applied to a more complex structure. In essence, the program generates a list of paths that are put into the vehicle computer. Once the vehicle arrives at a certain point, it can follow a series of specified path alternatives. Our single IM-6100 computer was not adequate, so we developed a computer system composed of three 6100s. Each one was dedicated to specific tasks: controlling the mission; controlling the vehicle's thrusters; and controlling navigation. A navigation computer handles all of the navigational functions: data acquisition; data processing and production of an x,y,z position and speed; and assuring reliability of the data. Each computer talks to the main computer, which has the mission algorithm and acquires system parameters, such as, temperature of the compass, heading, and depth. In effect, we have developed a distributive processing scheme containing specific components that perform well-defined tasks.

A modern microprocessor, the Motorola 68000 system, is being developed to extend the system capacity. The 68000 has the capacity for more sophisticated missions and for much faster processing of data. It also offers the potential of communicating in higher level languages (PASCAL or C).

Tests of these systems are underway at Lake Winnipesaukee and include evaluation of the navigation systems, the command computer, and mission algorithm. The interprocessor system and the communication philosophy are both completed and working. The first performance of the above mission is planned for October of this year.

One of the major problems we have encountered has been modeling of the navigation system. There were several system alternatives, which made it difficult to build a single model for an examination of the sensitivity of the navigation system to the system errors.

This coming year we will be trying to quantify errors in the navigation system. We also will be looking for possible errors in the vehicle's control system, including, in part, an analysis of the dynamics of EAVE EAST and the design of a control system that will take advantage of this information.

Another area we will examine is visual imaging. Ultimately, we would like to transmit real-time TV through the water. But, because of the limitation of the communication channel, it is obviously necessary to be "smart" on both ends. Data compression in this respect is unavoidable. The vehicle operator will know how to compress his data relative to what he knows about the mission the vehicle is conducting. If he can compress it sufficiently to put it into a low data rate acoustic link, he can then adjust the data as a function of its information to what the vehicle knows about the content. We do not yet have a strong feeling for what we can or cannot do in this area. We have investigated the feasibility of dealing with this through bandwidth compression. This year we also obtained (from Oceans Electronic Applications, Inc.) a CCD camera to test a bandwidth compression algorithm on actual underwater imaging, to see whether we can actually transmit video data through the water. (Our conversation with others in this field reveals a surprising scarcity of research into the imagery of ocean pictures or of their information content.) This algorithm can be implemented on a microcomputer, and it appears that compression ratios on the order of 20 to 30 are possible. We are presently modeling this algorithm and, once it is working we will investigate the possibility of putting the digitizer and frame-grabber together to implement the algorithm on a 68,000 CPU. On another 68000 system we will try to reconstruct the image in a remote operator's monitor. This will permit a qualitative comparison of the image we began with and the one we finished with.

<u>1981-1983</u>:

<u>Arctic Inspection Mission</u>: This program began recently. We are addressing the generic problems involved in performing a long range (possibly 1000 nm) under-ice inspection mission. The operating scenario now envisioned is to conduct a 10 kM mission to take acoustic profiles of the ice keel and the bottom. At this point we envision six echo sounders (five upward looking and one downward looking), operating on the order of 200 kHz with about 200 watts. A large part of this program entails investigating vehicle control to assure a high degree of reliability. With respect to the latter, we hope to make the vehicle "fail gracefully," if at all, rather than catastrophically, and to be friendly to the user. We will attempt to implement high level languages into the system--definitely PASCAL, C, if possible. We also hope to develop a recording device for the vehicle that will store engineering data and operating parameters during testing, as well as very large quantities of data during the mission. We will also investigate the application of bandwidth compression to the profiling data. We plan to use a magnetic bubble memory recorder (4 Megabit capacity) in the vehicle.

Microprocessor Development at Intel Corporation

Jeff Hawkins
Intel Corporation
Chelmsford, Massachusetts

The iAPX 186 and iAPX 286 processors are products that will be introduced in early 1982 by Intel. These are high performance evolutionary extensions of our current iAPX 86 product family. The 186 integrates many hardware components onto one chip. The 286 includes high level software features such as: task switching, memory management, and virtual addressing support.

Major components of the iAPX 432 processor family are available now, but the processor family will be growing for several years. The highlights of this family include incremental performance via software transparent multiprocessing, and a highly fault-tolerant design.

ARCS (Autonomous Remotely Controlled Submersible)

John Brooke
Bedford Institute of Oceanography
Dartmouth, Nova Scotia

The driving force behind the ARCS program is an urgent need for bathymetric surveys in the high Arctic where the area, in many instances, is ice-free for only a matter of weeks. We have looked at new techniques for surveying the Arctic, and one of the more promising techniques is an autonomous under-ice vehicle. A contract has been established with International Submarine Engineering, Ltd., Port Moody, BC, to provide such a vehicle. The performance goals of this vehicle are: 1) an endurance of 100 nm, a speed of five knots maximum and a maximum distance from the control station of about ten nm. While the vehicle will be truly autonomous, one feature of the system will include the capability of periodically checking its location and performance. Later, we hope to broaden the instrumentation suite to include seismic and sidescanning sonar. At this moment, the project is in the incipient stage and we are accumulating a base of knowledge by consulting with such organizations at the Applied Physics Laboratory, University of Wasington, and by gleaning information from the experiences of others, such as those of you at this symposium.

The program is currently funded for about three years.

EPAULARD

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La Seyne sur Mer
France

EPAULARD is designed to conduct deep water bottom photography and topographic profiling to depths of 6,000 m. It was launched in 1979 and has made 72 dives since that time; 40 of these dives have been to depths between 1,000 and 5,300 m. The vehicle is launched negatively buoyant and, once it has reached a pre-designated height above the bottom, it drops its descent weight and becomes slightly positively buoyant. A drag chain holds it a specified distance (three to seven m) above the bottom, according to the required resolution of the survey data control. EPAULARD's course is controlled by an acoustic link from the surface. Having completed its mission, the vehicle drops an ascent weight and returns to the surface.

Utilization of EPAULARD, to date, has proceeded from simple, straightforward missions, such as surveying the bottom of a canyon, to more complex missions involving fine-grained topographic delineation of an undersea relief feature. Recent at-sea operations included the deployment of a towed surveying vehicle (RAIE II) in combined operations with EPAULARD to obtain comparative data to better understand the strengths and weaknesses of the two systems.

Characteristics of EPAULARD are as follows:

- Depth: 6,000 m
- Speed: 2 to 2.5 knots
- Duration: 10 hrs
- Range: 12 nm
- Hull Material: Titanium
- LOA: 4 m
- Beam: 1.1 m

Height: 2m
Weight in Air: 3 tonnes
Propulsion: 1 horizontal thruster (and rudder)
Power: Lead acid batteries 48V, 18 kWh
Command/Control: Internal heading follower; acoustic command and measurement
Microcomputer system: 2 microprocessors 80 80; 3 UPI41 peripheral microprocessors
Communications: Acoustic link
Instrumentation: 35 mm still camera (5,000 exposures), temperature sensor, altitude sonar, depth and heading sensors
Launch/Retrieval System: Standard A-frame or crane

ANGUS
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During the past decade three unmanned cable-controlled submersibles have been built by this University: ANGUS 001, 1973-1975; ANGUS 002, commissioned in 1977 and used to establish an automatic guidance and control strategy for unmanned tethered vehicles over the period 1978-1981; and ANGUS 003 a modular version of 002.

The current research programme, from June 1981 onward, is concentrating on the automatic guidance and control systems, and the acoustic communication and signal processing systems required for tetherless vehicles.

Experience gained during the '002' programme has established a mathematical model of an open framed vehicle, defining the typical hydrodynamic characteristics of this class of vehicle. A hierarchical control strategy has been defined for both the tethered and an untethered vehicle using an acoustic navigation system. Manual control of the thruster demand is the basic level, with the closed-loop control of heading and depth forming the first level in the control hierarchy. In level 2, information from the instrument subsystem can be processed and the performance of the lower level control loops can be assessed. In a guidance, obstacle avoidance or an alarm mode, level 3 can define new objectives for the control loop and display information for the operator. Level 4 forms the man-machine interface, where the operator can assess the displayed data in tabular form or as a 3-dimensional representation of the motion of the vehicle. The 3-D display can take range and bearing data from the acoustic navigation system and give the operator an image of the vehicle position with respect to the ship and the trajectory of the previous path of the vehicle. The computer executes the control tasks in real-time, sampling the level 1 loops at a period of 100 msecs and the level 2 guidance loop at a period of 1 or 2 seconds. Software development for a control system of this complexity forms a substantial part of the system's research. To evaluate software for the control and guidance algorithms and the data communication link, the dynamic equations of the submersible have been programmed as a separate task within the control computer. This provides a simulation procedure to investigate the manoeuverability of the vehicle over a range of mass and drag coefficients, in addition to evaluating the control algorithms.

In the simulation mode of operation the motion of a free-swimming vehicle can be observed when driven automatically around a pre-defined path. An adaptive control loop has been designed to minimize the amount of control effort and, therefore, energy used to perform the mission, whilst minimizing the effect of the measurement noise. The trajectory can be data-logged by the control computer and plotted by the x-y plotter to give a record of the performance of a specified measurement noise.

The control strategy follows a procedure to first control heading and depth; then, predict the vehicle position using the approximate model during the sampling period, and, finally, estimate the position and correct the estimate at the end of the sampling period using the most recent measurment value. This correction takes into account the model inaccuracies and the sea current bias, and adapts the estimator gain to take into account the noise charateristics, before the new thrust vector is computed. The algorithm has been successfully implemented in a simulation mode and has been tested in deep water trials in June of this year.

The communication area covers the problems of thru-water signalling and video bandwidth reduction techniques. One area of communications is to employ the techniques used for wire guided torpedos where the wire is pulled out of a drum as it travels through the water. An optical fibre cable, when available, will be much smaller and lighter than those presently used and are suited to a small vehicle. As part of the communications research program a study has been recently carried out on a pulse frequency modulation system tied to an optical fibre link.

Research on underwater acoustics is currently centered on a comparison of modulation techniques and experimentation with high frequency, broad band transducers. In these, 600 kHz devices, a bandwidth of 150 kHz have been obtained, easily meeting a 10 kilo bits/second data rate with a possibility of a much higher rate. Stable platforms (quad-pods) have been constructed to enable reliable and repeatable tests to be made. Modulation techniques, including amplitude modulation, frequency shift keying, phase shift keying and differential phase shift keying have been compared with regard to a low digital error rate.

The other half of the communications study is the reduction of video bandwidth in values compatible with the acoustic channel, around 10 kilobits/second. This leads to slow scan TV techniques where a frame is stored and then retransmitted at a relatively low rate. Further studies with a slow scan TV developed by the Research Department of British Telecom will build up our knowledge in this area.

Another aspect of the project involves the investigation of techniques of transform coding applied to bandwidth reduction for video transmission. Here, the slow scan process is only one of many software routines developed to be run on an LSI 11/23 computer. In parallel with the image processing being developed, further hardware studies are centered on a low resolution TV charge-coupled device camera. Digital location of picture elements and analog gray level output, make this device an ideal research tool.

Future studies involve the interaction between a totally Free-Swimming Unmanned Vehicle (FSV) and a mother vehicle controlled by a surface cable. The most relevant application of the FSV would be in inspection of complex underwater structures, such as, rigs, platforms, and wellheads, where cable entanglement potential is high.

Sonar Image Processing: An Application of Template Matching Through Relaxation*

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Abstract

This paper discusses the use of high-level templates and relaxation techniques in processing side-scan sonar images. The images examined do not have enough resolution to identify the objects individually. Distances and orientations among groups of objects are stable, however, and provide the information necessary to unambiguously identify each object. The identified targets are then used to provide navigation information for underwater vehicles. Much of the work described is an application and refinement of established techniques, most directly those of Davis. Low-level filtering, template matching, relaxation and M* search are all discussed.

Introduction

This paper describes the use of template matching and relaxation in processing sidescan sonar images. Most of the basic ideas involved in combining template matching and discrete relaxation are refinements of the method discussed by Davis [2].

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This study extends their use to processing sonar images and uses knowledge specific to the particular task. Target detection, the techniques of template matching, relaxation, and M* search, and contributions of this study are all discussed, as well as specific details and experimental results.

The system examined processes sidescan sonar images for an underwater channel conditioning robot. The robot will map the location of large obstacles on a relatively smooth channel bottom, then check periodically to see if any of the objects have shifted or if there are new obstacles. Sonar serves two purposes: detecting the objects (called "targets") and navigating, based on identification of targets as known objects on the map. In practice, the primary navigation would probably be done by an inertial system, with sonar providing back-up and drift correction.

There are two basic parts to the sonar image processing. The first part is target detection: deciding which echoes are from targets and which are just noise, and reporting target positions. This is not generally possible to do with total accuracy. Some false alarms usually get through and some targets might be missed.

The second and more interesting part is target recognition. Given the location of detected targets, the system must either identify each target as a particular object on the map or classify it as a new object. Individual targets look very much alike, so identification must be based on distances and angles between groups of targets rather than on echoes from individual objects. It is here that template matching, at an abstract level, is used. If several identifications are possible, relaxation helps narrow down the possibilities. Finally, M* search picks the best identification for each target. In this case, "best" means not only the most likely for that single target, but also the most consistent for all targets.

Target Detection

The first task is to find the location of the targets in an image that is rather noisy by optical imaging standards. The images are generated by a Westinghouse sidescan sonar. A sidescan sonar looks at right angles to the direction of the travel of the vehicle, constructing an image row by row as the ship moves forward. The sonar looks down and out at an angle, so it misses objects directly below the vehicle but has a good view of objects sticking up from the bottom off to the side. The images generated are eight-bit images, with about six bits of reliable data, and are 1000 pixels square. There is much noise, with scattered reflections off the bottom ranging over the whole dynamic scale, giving a strong salt-and-pepper appearance to the image. Various preprocessing filters and smoothing algorithms were used to try to clean up the image. None of them succeeded in eliminating noise without also eliminating targets.

Targets (reflections from objects) appear as bright blobs, about five or six pixels across. Each target image has a long shadow (up to 50 pixels or more) trailing directly away from the sonar transducer. Length of the shadow is a function of a number of variables: height of the vehicle above the bottom, height of the obstacle, and distance from the vehicle to the object.

Neither the bright target images nor the dark shadows by themselves are enough to pick the targets out of the noise. Together, however, they provide enough information to do a fairly accurate job of detection.

All targets are about the same size, and all their shadows fall in the same direction (directly "behind" the target as seen from the sonar transducer). This makes it possible to convolve the image with a filter that has maximum response when it overlays a target and shadow. A relatively crude step filter, with weights of +1,0, and -1, is adequate and can be convolved efficiently. The filter can be described graphically as

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+++000-----
+++000-----
+++000-----
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where the value calculated is the sum of the values of the pixels underlying the +s, minus the values of the pixels underlying the -s. As the filter is moved across the image, the highest values result when the bright, high-valued pixels of a target lie under the +s, and only dark shadow with low values lies under the -s. The 0s are necessary because, typically, there is a fuzzy edge between target and shadow. If the value calculated for a given point exceeds some threshold, the coordinates of the center of the + region are reported as a possible target location. Another program takes this list of points and clumps adjacent candidate points into objects, reporting row and column coordinates and number of points in each object. This process also uses a threshold, rejecting objects with only a few points as probably being noise. Aspect ratio, left- or right-sidescanning, and other sensor-dependent variables are taken care of at this point.

The straightforward approach to convolving the filter with the image is computationally expensive. Each point in the image would require, for the filter shown, nine additions and fifteen subtractions. A better algorithm keeps column sums and incrementally updates the total each time the filter is shifted [3]. This cuts the convolution down to only three additions and three subtractions per pixel for an arbitrarily large filter.

Template Matching

Once the targets are detected, they need to be identified as some known object on the map. A target can almost never be identified in isolation. There can be more differences between the appearance of the same object in two different images than between different objects in the same image. There are problems with noise, specularity, different distances between target and transducer, and views from different directions. Consider, for example, the difference in echoes from a "D" shaped object when viewed from the left or from the right. Since information about single targets is so unreliable, it is necessary to use other information sources. Distances and orientations between targets are generally much more reliable and much more stable from one image to the next. This information is used to drive a high-level template-matching scheme.

Template matching works by comparing an image, or parts of an image, with known objects. Classical, low-level template matching works with the digitized image directly, comparing it pixel by pixel with a template. The image and the template match if the difference between their pixels is less than some threshold.

Template matching can also be used on a higher level, matching description to description rather than pixel to pixel. In sonar image processing, the actual image is abstracted to the coordinates of the targets, and forms a template described in terms of locations, distances, and orientations. Note that the image is used as the template in this case, since it is smaller than the map. The objects on the map are described in similar terms. In fact, the map may have been constructed from a previous pass with the same vehicle and sonar imaging system. Quality of a template match is then a function of how much the template (image description) must be stressed--stretched, twisted, and shifted--to line up with the map. Hence the name "rubber template" for this kind of matching. A fringe benefit of this kind of map and template is that very little storage is needed; only three integers (row, column, and intensity) per target, for about 10 to 20 targets per image, rather than the megabyte of memory necessary to hold the entire image.

A match between the template and the map is an identification of each target, or an indication that some targets are not on the map. To make the process more efficient, template matching is done in stages. First, a rough approximation is made using only part of the information available. This usually leaves several candidate matches, that is, more than one possible map identification for each target. Then, more constraints are applied using relaxation to discard the less likely matches. Finally, the remaining template matches are evaluated and the one that induces the least stress in the template description is chosen as most likely to be correct.

A few things are known apriori. Other navigation systems can provide a rough idea of present position and a quite accurate heading. So it is possible to calculate an approximate position for each target. This means that the map objects that have to be considered as possible identifications of each template (unknown) object can be limited to those within some small distance of where the robot thinks each object actually is.

The first step in template matching constructs a list of possible identifications, each a target-map object pair. A pair is created only if the position of that object on the map is sufficiently close to the calculated position of that target, and pairs are given a weight based on how close the actual distance is. Note that any given map object or target can be part of several different pairs, since a target may be near several map objects.

The pairs contain information only about the location of single targets and map points. This usually isn't enough to unambiguously identify targets. To incorporate more information and create a framework for further processing, the list of pairs is turned into a graph. Each pair becomes a node of the graph. Information about relationships between pairs of targets and pairs of map points goes into the edges of the graph. Two nodes are linked only if the corresponding distances are within some tolerance. In other words, if T_i-M_i and T_j-M^j are two nodes (that is, two target-map pairs), they will be linked if the distance T^i-T^j between targets is about the same as the distance

M^i-M^j between corresponding map points. The idea is that if the distances are inconsistent, at least one of the identifications must be wrong.

To summarize, the terms "node," "target-map pair," and "possible identification of a target" are used interchangeably and all refer to the calculated location of a target. An example would be "target at row X^1 column Y^1 in the sonar image, object on the map at X^2 Y^2," which indicates that the particular echo might be coming from a certain rock that is at a particular place on the map. Furthermore, the existence of a link between two nodes implies that both nodes could be correct identifications of their respective targets without having to stretch distances too much.

<u>Relaxation</u>

The first step of template matching uses only some of the information about an image and will almost always result in several possible identifications for a given target. Recall that the information in the nodes themselves is only the calculated position of the targets. Relaxation is applied to use information from the links between nodes (that is, distances between pairs of targets and between corresponding pairs of map points) to delete nodes.

In relaxation, the value of each node in a graph is a function of the values of its neighbors. For example, we can derive the temperatures at points inside a metal bar by modeling the bar as a lattice graph with known temperatures at the surface. A first approximation of the temperatures at any given point is the average of the temperatures of its neighbors. Successively finer approximations can be calculated by averaging the updated values of the neighbors until the change from one iteration to the next is sufficiently small.

The relaxation used in template matching is "discrete" rather than "continuous" as in the example above. Rather than increasing or decreasing a node's value, the node is either retained or deleted. Again, this is a function of the other nodes to which it is linked. A node is said to be "supported" by its neighbors if their weights are enough to prevent its deletion. Since deleting one node may remove enough support from one or more of its neighbors to cause their deletion, the process may be repeated until a stable graph remains.

If the position of each target were calculated exactly, there would be a node for each correct target-map pair. Moreover, each correct node would be connected to all the other correct nodes, since the target-target and map-map distances would match exactly. There could be other spurious nodes, and they would probably have links to at least some of the correct nodes, but not to all. So the search could simply find the maximal clique (fully-connected subgraph) in the graph, report those nodes as the correct identifications, and discard all others.

In general, though, some nodes, links, or both will be missing because of errors in calculated target positions. It will still be the case that almost all correct nodes will be linked to almost all the other correct nodes, since the respective distances will be nearly correct. Discrete relaxation may be thought of as finding the largest almost-clique, useful for imperfect graphs. Each node is checked to see if it has enough links (that is, if it is consistent with enough other identifications); if not, it gets deleted. Furthermore, neighbors are not simply counted. Rather, the weights of the neighbors are summed and that total is checked against a threshold. In this way, nodes that have a high probability of being correct based on position (that is, nodes with a high weight) contribute more to keeping a neighbor than do less probable nodes. Since deleting a node also deletes all links to that node, one or more of its neighbors may then fall below the threshold. So the entire process is repeated until a stable subgraph remains.

Selecting a threshold poses something of a problem. If there are a large number of spurious nodes at the beginning of the relaxation process, even incorrect nodes may have many neighbors. On the other hand, by the end of the deletions there would ideally be only the few correct nodes, each with only that number of neighbors. So a variable threshold must be used, set according to the number of nodes remaining at each iteration. The threshold can be lowered automatically if a stable subgraph is reached with far too many nodes, or raised and the process repeated, if too many nodes are deleted.

Relaxation based on nodes and links will eliminate most of the incorrect nodes, but not all of them. The information used up to this point comes from calculated position of individual targets (creation of nodes), from distances between pairs of targets (creation of links), and from consistency of those distances (relaxation). The next stage looks at orientations and angles formed by three targets (two links from the same node).

The two template-map pairs at the ends of a link define a line segment in the template and an equivalent one in the map. Mapping the template line segment onto the map segment gives a four parameter transform: the line segment can be stretched, rotated, shifted in X, and shifted in Y. These four parameters are calculated for every linked pair of nodes, and that information is stored with each link; relaxation is then used on the links. Where before, relaxation checked for consistency between nodes (position of targets), in this case it is used to check for consistency between links and, therefore, between groups of nodes.

In a perfect match, each pair of correct nodes would produce exactly the same four parameters. In other words, if the template needed to be stretched, rotated, and shifted by certain amounts to match the map, the line segment connecting any two targets would, itself, have to be stretched, rotated, and shifted by those same amounts. If one of a linked pair of nodes represents an incorrect identification, then even though the length of the line segment might be nearly correct (it must have been, in order to get by the first relaxation step), the rotation and shifts will be wrong. So relaxation in this case compares a link with all other links having a common endpoint. If the four parameters of a transform attached to a link are each within some value of the parameters of an adjacent link, the links are consistent. If a link is consistent with enough other links, it survives; if not, it is deleted. Note that what is being looked at is not the value of an individual transform; rather, it is the difference between two transforms. A given line segment can be rotated and shifted by an arbitrarily large amount, as long as other line segments are rotated by nearly equivalent amounts. Just as in the case of relaxation over nodes, deleting a link might lead to the deletion of one of the adjacent links. So the relaxation is iterated until only stable links remain.

Deleting links reduces the number of neighbors of the formerly linked nodes, perhaps to the point that some of them may no longer have enough consistent neighbors. So the next step is to run the node relaxation process again. The result is a stable graph, usually with very few spurious nodes.

Search

Even after the template matching and relaxation steps, there can be more than one plausible identification for a given target. M* search is then used to pick the best set of identifications.

M* was first described by Barrow and Tennenbaum in [1]. It works as follows. Check the list of nodes, looking for some target with more than one possible identification. Call the M* procedure recursively on a series of new lists, each the same as the original list but containing only one of the conflicting identifications for that target. When there is only a single node for each target, the remaining nodes describe a candidate match. This match is evaluated by assessing the stresses in the template as follows. The "cost" (stress) of the match is incremented 1) for each unidentified target, 2) as a function of less than perfect positional matches (from node weights), and 3) as a function of distances between a pair of targets not matching the distance between the corresponding map points (the link "stretch" parameter). If the total cost of this match is less than the total cost of the best match previously evaluated, this match replaces the former best match.

It might be that some nodes survived the relaxation process by being linked to two conflicting nodes (that is, nodes with different identifications for the same target). This can be discovered, and those nodes deleted, by running the relaxation process each time the M• routine generates a new list of nodes. Often after relaxation, the subgraph formed by that list of nodes and their links will collapse, ruling out that search path and saving search time.

Note that the M• search process would work correctly if it were invoked on the original graph. Relaxation is much less time consuming, though, and considerably reduces the size of the subgraph that must be searched. On the other hand, relaxation might occasionally throw out nodes that actually belong to the best possible match. So there is a tradeoff between running time and confidence in the result.

Finally, it is possible to use the results of all this processing to provide accurate information for navigation. Given identifications of several targets, it is relatively easy to calculate the four parameters of the global transform that maps each target as closely as possible to its map location. Then, knowing the ship's location and heading relative to the image, the true map coordinates and heading of the ship are easily obtained.

<u>Experimental Results and Further Research</u>

The experimental study dealt with six sonar images of the same area: three generated on passes up the channel, and three in the opposite direction. One of the images was used to generate the map. Matching the other two images made in the same direction, with vehicle position known to within 100 pixels in each direction, produced the correct identification for each target, and gave heading and position correctly. Matching images made in the other direction was a little more difficult. The mathematics of flipping, rotating, and shifting the image posed no problem. But there were differences in the scaling of the two sets of images along the direction of travel, apparently caused by a current. Visual inspection of the images shows that the three taken in one direction are compressed in the direction of travel, while vertical distances between targets seem to have been stretched out for those taken in the other direction. There are two solutions to this problem. The easier, from an image processing point of view, would be to get more accurate information on absolute vehicle speed and correct the images based on that. The other possibility would be to change the template to allow more stretch in the direction of travel than perpendicular to the vehicle, and to place more emphasis on consistent stretch and less on absolute positions.

Another problem to be worked on is automatic determination of thresholds. The first place this arises is in target detection. Apparently the calibration of the scanners used in one direction was significantly different than the calibration of the other scanners, so the second set of images was of much higher intensity. The target detection parameters, carefully tuned to the first set of images, produced more spurious targets than real ones when applied to the second set. Adjustment of the parameters to suit this set of images was not a big problem, but it was impossible to find a set of parameters that worked correctly on both images. Some type of histogram-driven automatic threshold would be a good idea. Other variables that have been experimented with, but could use more examination, include size of the filter and number of points in a clump necessary to report it as a target.

In the relaxation steps, there should be a way to adjust thresholds as a function of confidence in the reported positions. If the vehicle's position is accurately known, ocean currents are at a minimum, and the image is sharp and well detailed, it should be possible to restrict the range of possible identifications for each target. Some of this is done manually now, by asking the user of the program for maximum allowable stretch, for instance. Also, node and link deletion thresholds, which are now only a function of the number of nodes, should be adjustable if too many or not enough nodes are left at the end of the process.

Weighting the cost function of the M• search is also a problem. How much more cost should be assigned, for example, for an unidentified target than for an identification that stretches distances? Currently, the weights are set in a rather ad hoc fashion. There might be no good, scientific way to set them; if not, trial and error will have to suffice.

Finally, the whole process should run faster. As an experimental project, much of the coding is done in a straightforward, understandable, but inefficient style. In order to run this onboard an autonomous vehicle, running time as well as storage space will have to be reduced. Most of this will be relatively easy once the design is frozen.

Conclusions

Template matching and relaxation provide an accurate and efficient way to recognize objects in certain kinds of images. The important image characteristics for the style of processing described in this paper are 1) image reliably separable into individual parts, 2) those parts not recognizable by themselves, and 3) some relationship between the parts that is stable in different views of the same area while being distinctive enough to provide reliable identification.

Davis, on whose work much of this is based, used template-driven relaxation to recognize contours of islands. He approximated the contours as polygons and did his recognition based on relative locations of vertices and their angles. Reliably decomposing the image posed problems: a small change in curvature could cause a large shift in the location of a vertex of the polygon. His data could also be arbitrarily rotated, which added another complication. Even so, the distances between vertices, the size of the angles, and the ordering of the vertices along the contour were enough for accurate identification.

Sonar image processing, as used in channel conditioning, seems a natural application for these techniques. The image decomposes very nicely into separate targets, each nearly indistinguishable from the others. Orientation and position are roughly known, so there needn't be concern about rotation invariance. Nor should there be gross differences in scale. As a result, positions of targets and distances between them provide clues not available in Davis's island contours. Possibly most important, the distances and angles between targets, perhaps corrected for ocean currents, are stable, reliable, and recognizable.

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Autonomous Vehicle Activity at Hydro Products

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TV Cameras

Hydro Products builds a wide variety of underwater TV cameras for general and specific applications. These include standard Vidicon cameras such as the TC-125 and TC-125-SIT. There is also a TC-125-SDA (a solid state sensor resistant to burn and high light intensity). Special purpose cameras built at Hydro Products include radiation tolerant cameras, such as the TC-215-SN, and the TC-135 (a small diameter, 2.9", with a scanning optics arrangement for inspection of nuclear reactors); and the PATZ (for pan, tilt, and zoom) camera. This camera provides a camera-to-subject distance measurement readout once the subject is in focus. Other cameras include the Surveyor Diver Helmet-mounted TV, and a modified version for use on the RCV-150. The RCV version is mounted on a pan and tilt mechanism and employs a Newvicon tube for low-light-level sensitivity. The latest camera development at Hydro Products is a color TV called 'Hydro Color' which has automatic color compensation.

Hydro Products also produces a wide variety of underwater lights including quartz Halogen, Mercury vapor, and Thalium Iodide type lamps of different power outputs.

Microprocessors at Hydro Products

Hydro Products is using the PACE microprocessor in its RCV-150 vehicle. The PACE is a 16-bit machine built by National Semiconductor. The PACE INS 8900 is replacing the old-style PACE and is used on several systems. Last year we acquired the capability to do software development for Z80 microprocessors and are now using the Z80 microprocessors in the color TV camera and in several vehicle control systems. There is now a separate Microcomputer Group within our Engineering Department that is responsible for present and new microcomputer development activity.

Autonomous Vehicle Activity

Hydro Products has just started some generalized studies for application of autonomous vehicles in the industrial and scientific fields. We are focusing on long range, long duration (days) systems that are highly autonomous and do not employ acoustic or fiber optic communication links, except as back-up, or in some cases, supervisory control. Applications that we will be aiming toward include Arctic survey and deep ocean petroleum exploration.

We have developed and are using a computerized vehicle design model that facilitates the preliminary design of autonomous vehicles. The program allows a designer to quickly and efficiently size a vehicle, based on performance requirements and design constraints. The designer can also carry out comprehensive sensitivity analyses to determine the effect of variations in various parameters on the vehicle configuration and performance. Thirty-one independent variables (e.g., range, mission time, payload, power type, energy type, hull form, structure type) are accepted by the program.

Dependent variables calculated by the program include all elements of a mass properties report, power plant characteristics, fuel requirements and vehicle principal dimensions.

We now have a six degree-of-freedom-vehicle-model running on our HP1000 computer to allow us to do vehicle dynamic simulations. Other work in the area of autonomous vehicles includes the study of navigation, communication, and artificial intelligence technologies.

(The speaker described the Hydro Products RCV-150 vehicle and provided an overview of the RCV-175. He also showed a videotape of the RCV-150 performing tasks with its manipulator in the Hydro Products Test Tank. A reference was sited for a complete description of these manipulator capabilities: Eppig, S.H. 1981. Vehicle Maneuverability Augments Remote Controlled Manipulator Task Capability. Proceedings IEEE Conference, OCEANS '81, Volume 2, pages 1143-1149. Editors note.)

Survey of and Problems With Acoustically Pulsed Transponder Navigation Systems*

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Abstract

This paper presents a brief survey of ideas about acoustic transponder navigation based on experience with working systems used in oceanographic research at the Woods Hole Oceanographic Institution (WHOI). These systems have been designed to work effectively because of the presence of an operator. The vehicular navigation has its base of operations aboard a surface ship that sets a network of transponders and surveys the net. The survey data is reduced onboard the surface ship to produce the relational positions for navigating an underwater vehicle. In most cases, the underwater vehicle is actually navigated from aboard the ship. If it can be assumed that the setting and surveying of the transponder net is independent of navigating an underwater vehicle, techniques can be logically extended to navigate a remote, independent submersible by acoustically pulsed transponders. Problems of acoustic pulse transmission and reception, environmental noise, signal-to-noise ratio, and considerations of effective range must be overcome to nagivate effectively. Once these are overcome for a remote underwater vehicle, the problem is reduced to one of guidance.

*This paper is a more formal presentation of a talk presented by Mr. Loud to the Unmanned Untethered Submersible Technology Symposium, Sept. 21-24, 1981.

To navigate an underwater vehicle within a transponder net, the net must be installed and surveyed. Several techniques in surveying and calibrating a transponder net are discussed. In many respects, this is a more complex task than navigation within the net. Planning the layout and setting the transponders, then collecting the proper set of survey points is a time-consuming task, but if accomplished properly, the data can be used to calibrate the relational parameters of the net accurately (within 12-20 cm).

Introduction

Most of the ideas presented here are based on two of the acoustically pulsed transponder navigation systems in use at WHOI: Acoustically Navigated Geological Underwater Survey (ANGUS) system and ALVIN Navigation (ALNAV) system. The ANGUS vehicle is a tethered camera platform and the ALVIN vehicle is an independently maneuverable, manned submarine. These two systems use identical acoustic hardware and share the same concepts of operation required to navigate a ship, FISH, submarine, or sonobuoy. The computers used to compute position fixes are different and, therefore, use different software. These systems were designed to be controlled by an operator and, therefore, little emphasis was placed on automatic navigation. The requirements for recording and displaying data require the presence of an operator to control the system in accordance with the needs of the researcher. Highlights of these systems are presented along with some of the limitations and technical difficulties encompassed by such systems.

The Acoustic Navigation Problem

Of the two types of acoustic transponder navigation systems, the Range-Bearing or short baseline system is most useful for locating a submerged target. If a single transponder or continuous wave (CW) beacon is placed at a target, a training direction finder or a phased tansducer can be used to obtain the bearing of the target relative to the navigated vehicle. Slant range can be obtained if a pulsed transponder is located at the target; if the depth of the transponder is known, the horizontal range can be obtained. This method is useful for locating a pipeline, recovering a transponder, or tracking an underwater vehicle (used for launching and recovering ALVIN). In addition to the limitations and technical difficulties associated with acoustic signaling discussed under Range-Range navigation, the accuracy depends on how finely the bearing can be measured (typically, one to five degrees). Thus, the tracking vehicle's positioning (cross range) error is dependent on range to the target. (See Figure 1)

The Range-Range or long baseline method of acoustically pulsed transponder navigation requires multiple transponders. A vehicle navigates within a network of transponders and relative to the transponders. Slant ranges are "measured", and three dimensional triangulation is used to compute the relative position of the vehicle within the transponder net using the known baseline lengths and transponder depths. (See Figure 2)

Unfortunately, slant ranges from the vehicle to each transponder cannot be measured directly. Instead, the round trip travel time of a pulse of oscillating acoustic energy (see Figure

3) is measured. Each transponder is tagged by an individual frequency to identify it from all others. Filtering and discriminating this acoustic pulse from other acoustic noises in the ocean environment is a sophisticated task for analog electronics. Pulse identification is dependent on signal level, signal to noise ratio, and receiver sensitivity and gain. The effective range of the acoustic pulse is dependent on environmental limitations and the laws of physics. A lower frequency pulse travels a longer distance, and a higher frequency pulse yields better resolution and, therefore, a more accurate position (typical frequencies used for ranging are 7-16 KHZ). Other complexities in the ocean cause difficulties in signal transmission such as: salinity, density, temperature, and pressure. These can be reduced to local variations in sound velocity within the water column. These variations cause the ray path to be a little longer than the straight line path and insignificantly longer in the deep ocean. But in shallower waters, more curving occurs and in very shallow water the signal might bounce or reverberate while traveling from the transponder to the vehicle. Submersibles experience this phenomena much less frequently than does a vehicle operating on or near the surface, but it is always a potential difficutly.

The purpose of pulsed transponder navigation is to measure a travel time of an acoustic pulse as it traverses the ocean environment. Considering the simplest case, that of navigating a ship (see Figure 4), an omnidirectional pulse is transmitted by the ship's transducer; received by each transponder, which transmits its own omnidirectional pulse identified by a specific

Figure 1. Range and Bearing to a Transponder

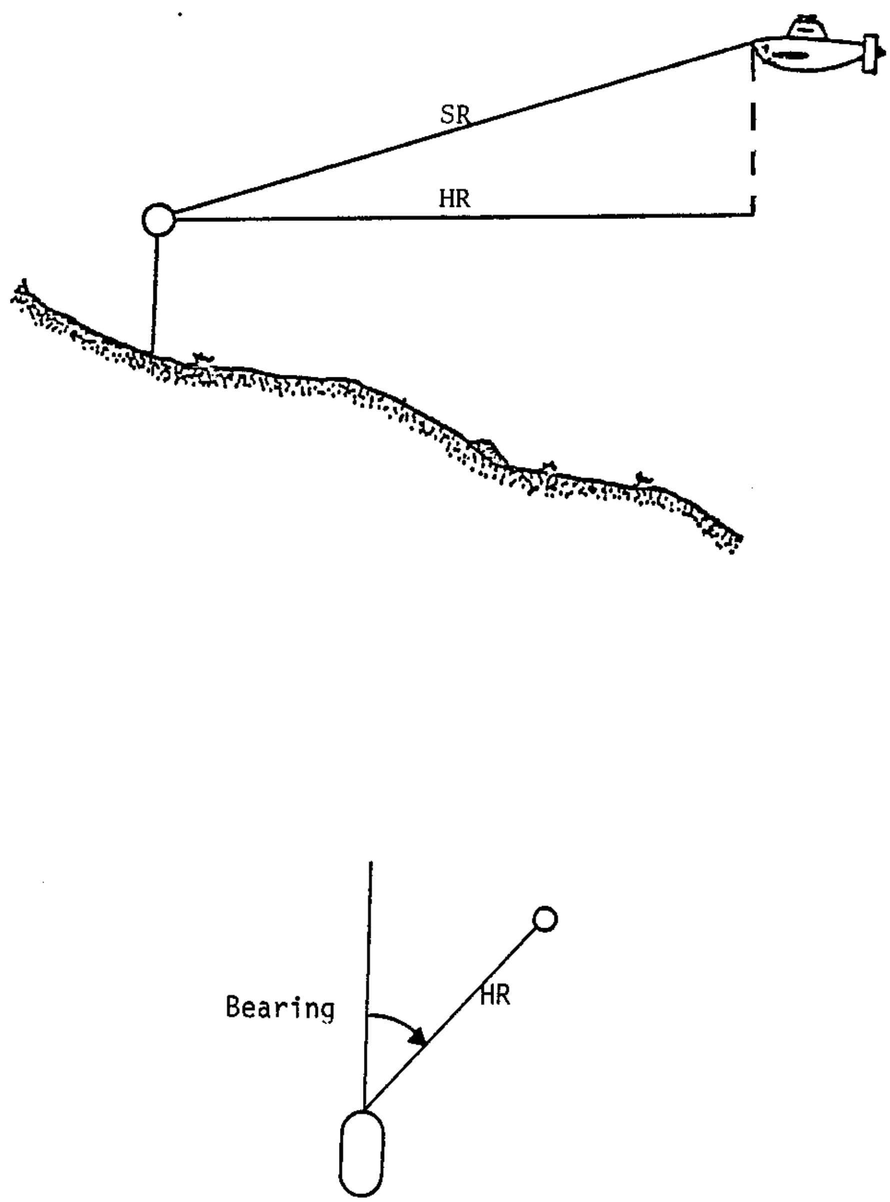


Figure 2. Positioning A Submarine

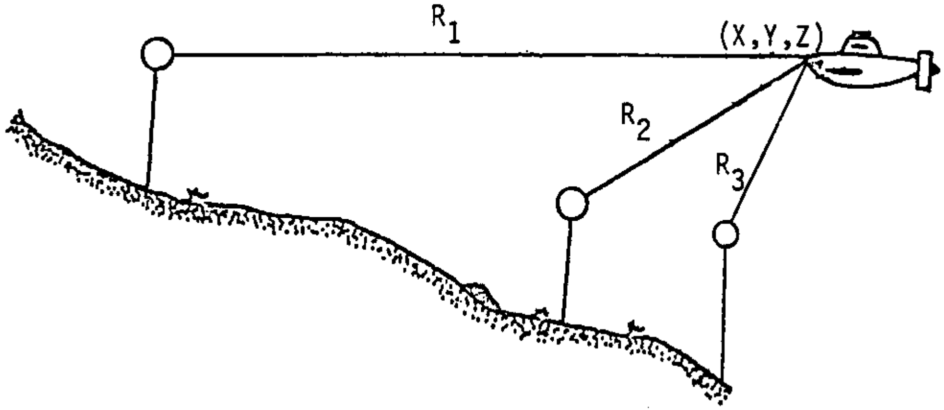


Figure 3. Acoustic Pulse

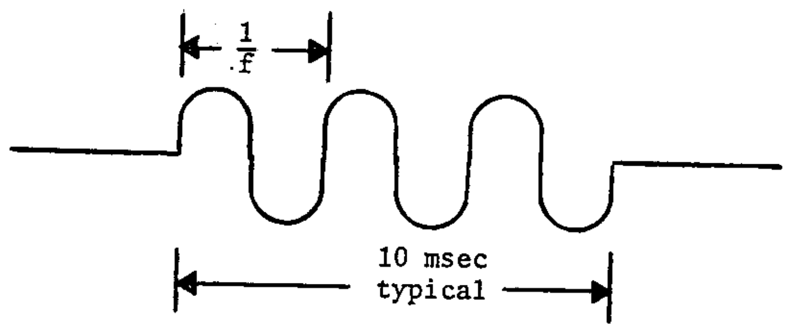
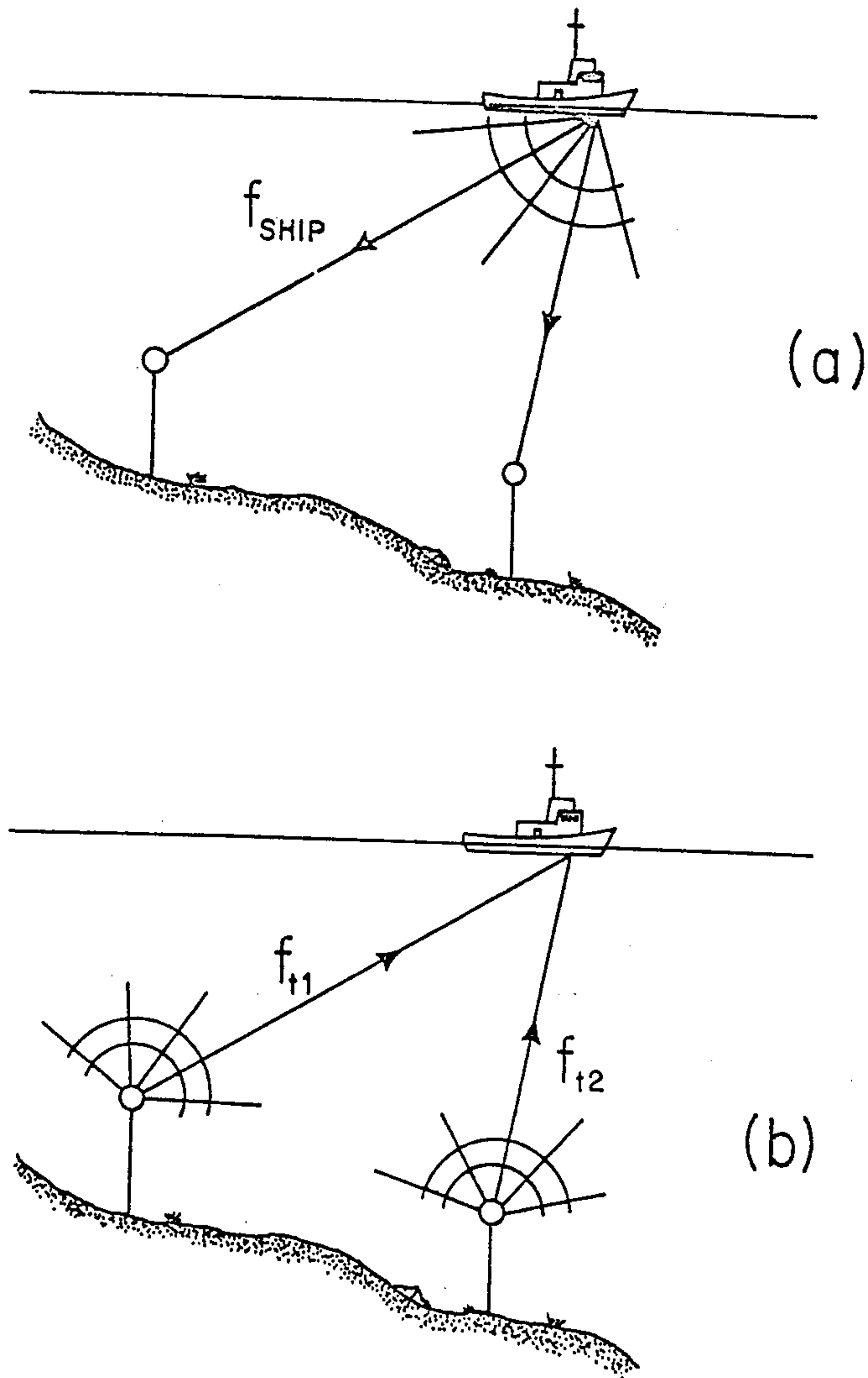


Figure 4. Ship Cycle



frequency; and is then received by the ship's transducer. Electronics of the acoustic receiver aboard the ship identify and separate each received frequency into a separate channel measures the round trip travel time.

Conceptually, this is relatively straightforward. However, the ocean environment presents many difficulties for an acoustic pulse traveling in such a medium. Terrain and structures within the water column block and deflect the pulse. Biota absorb and generate acoustic energy; whales and porpoises, in particular, communicate by using the typical frequencies for ranging and appear to mimic these pulses. The pulse traveling through this inhomogeneous medium is distorted and is also modified by reflections from small particles and plankton. Ship noise caused by engines and propellers causes the hull and, thus, the water, to reverberate. Water noise and sloshing are caused by friction created by the moving ship, as well as by cavitation from the ship's propulsion. Many of these factors simply limit effective range by decreasing the signal-to-noise ratio of the received pulse. The effective range of the acoustic pulse is dependent upon attentuation, frequency, and ray paths.

Other sources of error affect the measured travel time. Electronic time delay variations within the various transponders and transducers and small variations in travel path introduce jitter. The jitter caused by tides, waves (surface and internal), currents, and sway of a transponder at anchor also produce positioning errors.

Ray paths can lead to gross positioning errors if they are not taken into consideration. An acoustic pulse almost always travels a longer distance than the straight line path but not necessarily in a longer time. In the deep ocean, a pulse traveling from the surface to the bottom may have a travel time approaching that of the straight line. A pulse traveling along a deep near bottom path might do the same. When a pulse travels horizontally and vertically within the water column, ray paths must be seriously considered. One important aspect is that effective range is limited by the height of the moored transponder. (See Figure 5) An example of this phenomenon is shown in Figure 6. The multi-path phenomenon occurs when a ray bounces or refracts between the bottom and the surface or within layers of density variations when traveling between water depths. These extreme possibilities are shown in Figure 7. All of these difficulties require that proper consideration be given to modeling of ray paths to navigate accurately.

Once the round trip travel times to each transponder have been measured, they must be converted to slant ranges. The one-way travel times from the vehicle to each transponder must be determined with proper consideration given to transducer and electronic time delays in signal processing. Converting these one-way travel times to slant ranges is dependent on modeling the ocean environment. A sound velocity is necessary to convert travel time to slant range. Other modeling is dependent on the application and accuracy expected of the system. Proper consideration should be given to correcting for velocity of the vehicle, variations of currents within the water column, sound

Figure 5. Deep Water Limiting Ray

R MAX	HT
1000 M	5.4 M
2000	22
4000	87
6000	195
8000	350
10000	545

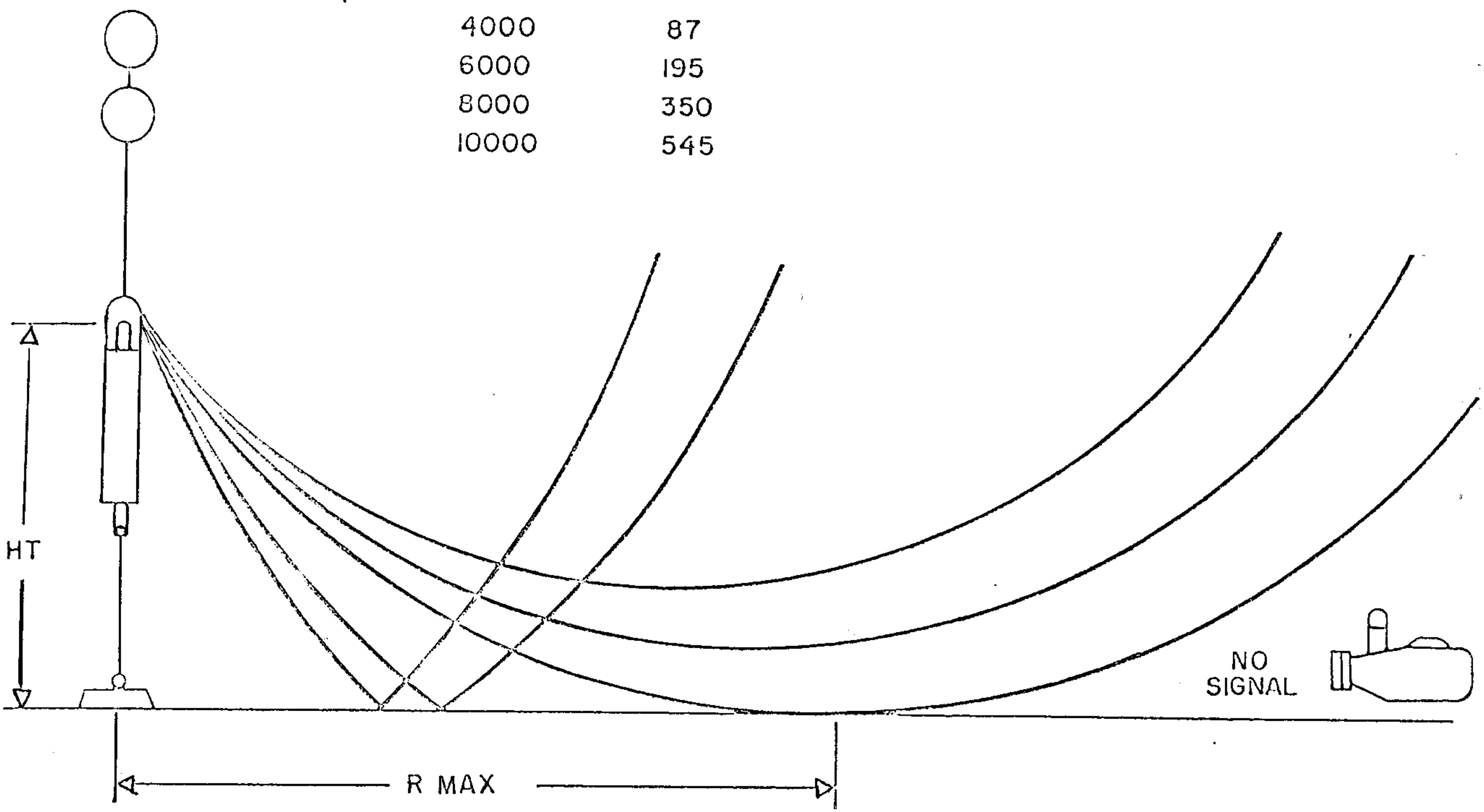


Figure 6. Ray Path Miss

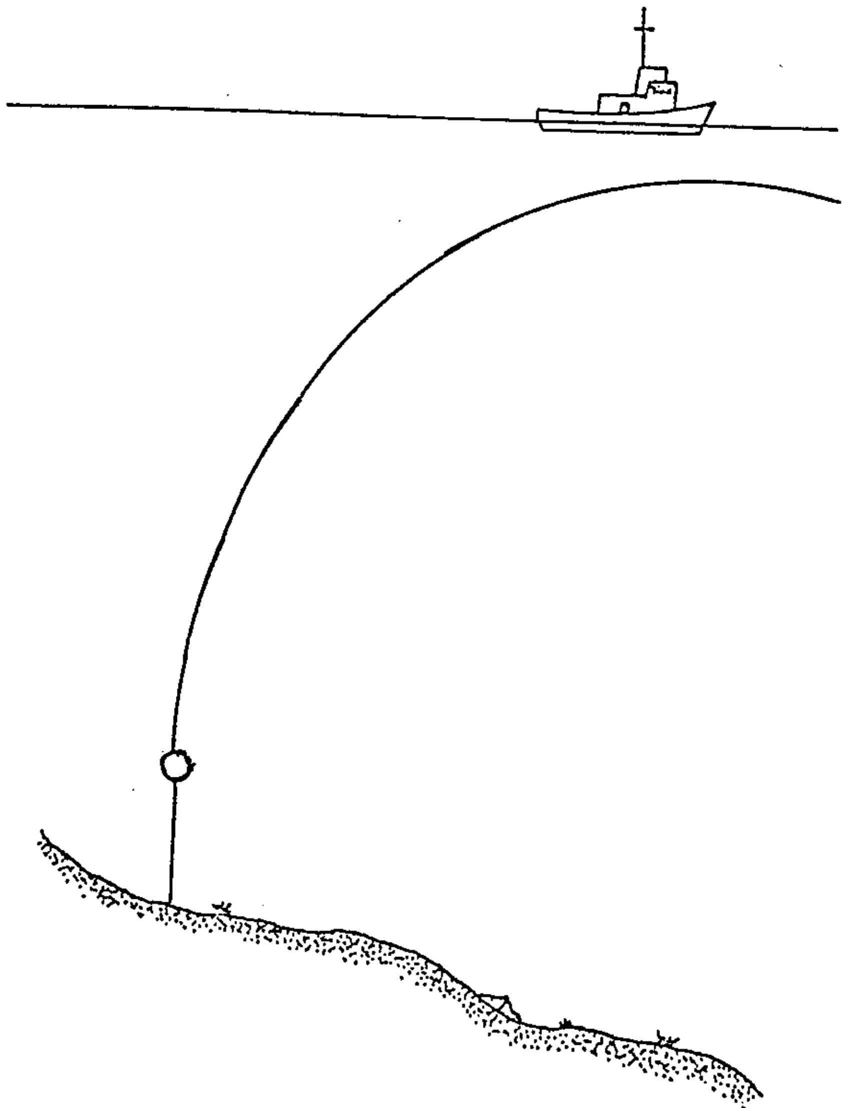
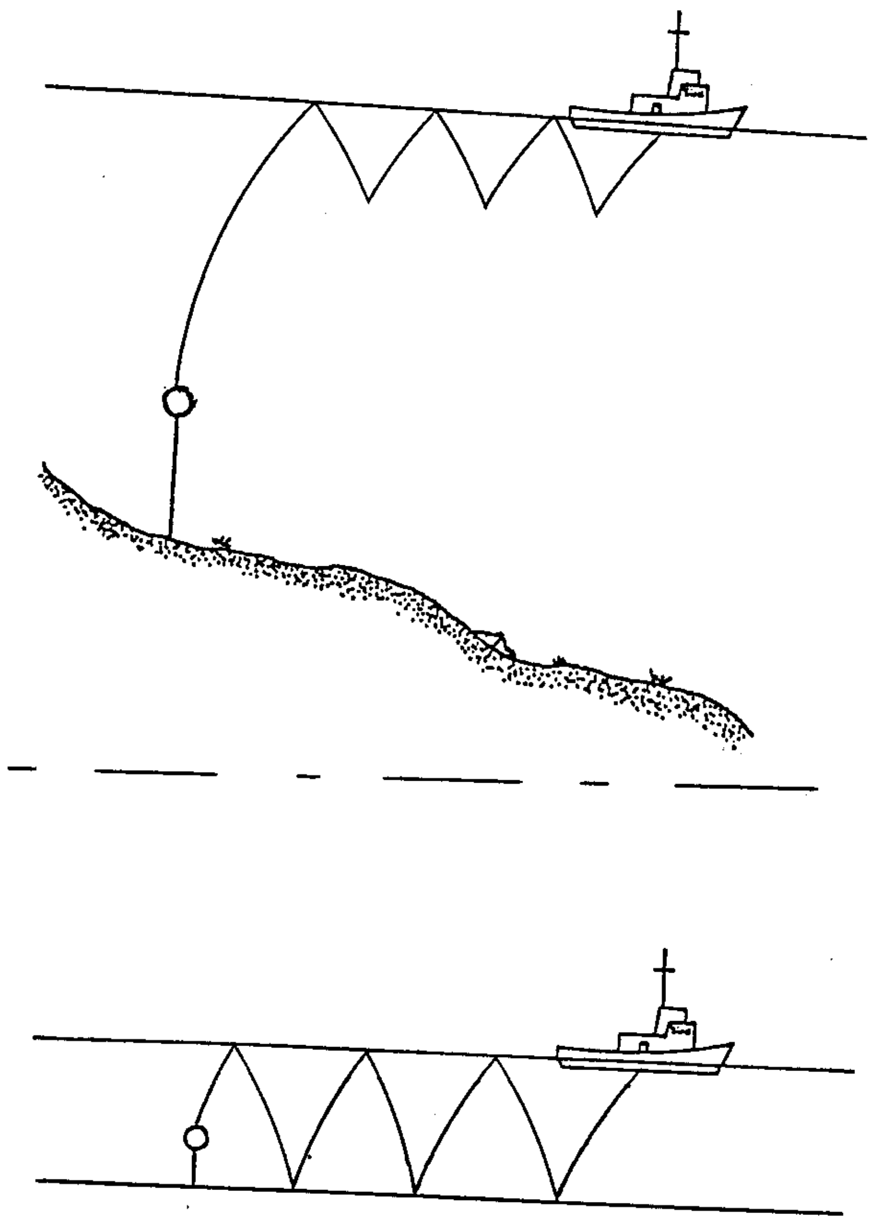


Figure 7. Two Examples of Unusual Ray Paths



velocity variations, ray bending, predictable signal bounce (surface bounce) (see Figure 8), and range gating of the travel times. With all of these considered, there can still be positioning errors owing to jitter in the travel times, which can be caused by swaying of the transponders at anchor or signal paths that include a short bounce. Tides and waves affect the depth of the water column; these will average out over the long term, but they can affect short term accuracy. Normally, the methods employed sort through the measured travel times and discard all but the "correct" ones. Similar methods are often used for slant ranges and, then, a navigation fix is computed.

Basically, there are two mathematical techniques for three-dimensional triangulation to determine a relative position using slant ranges: deterministic or non-linear regression (least squares). The deterministic method uses two slant ranges to determine the X-Y intersection at a specified depth (see Figure 9) and, through apriori knowledge, the position is chosen with respect to the baseline pair of transponders corresponding to the slant ranges. The least squares technique uses all available slant ranges to estimate the "best" intersection. (See Figure 2) To estimate an (X,Y,Z) position, a minimum of three slant ranges is necessary plus an independent depth. A three-by-three matrix (as well as other matrices) is created, inverted, and solved iteratively until the sum of squares error is minimized. This sum of squares error is computed from modeling slant ranges based on estimated position and the "measured" slant ranges. This is the better method when considering an unmanned remote vehicle.

Figure 8. Interrogation of a Bottom Transponder Via Surface Bounce

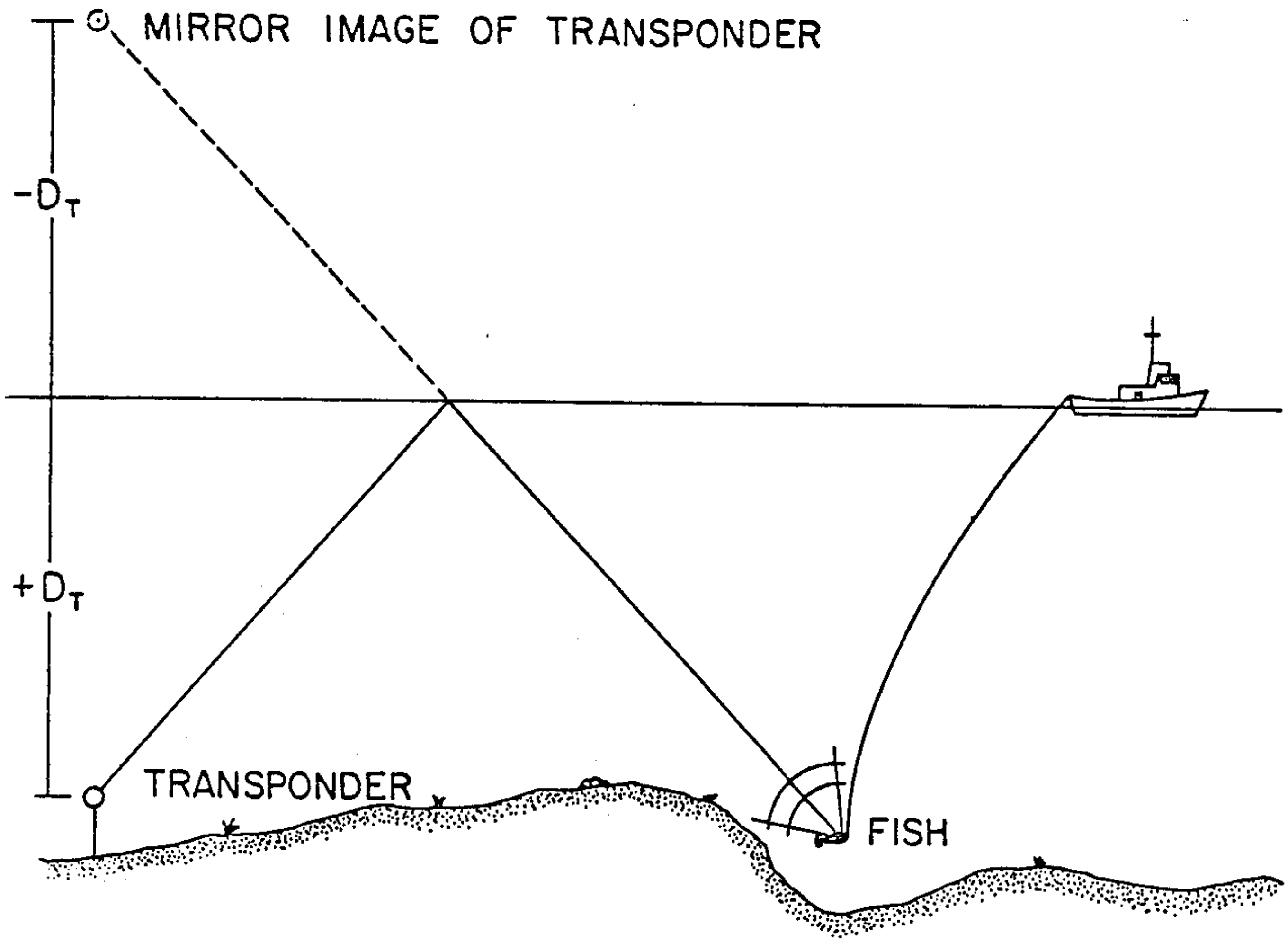
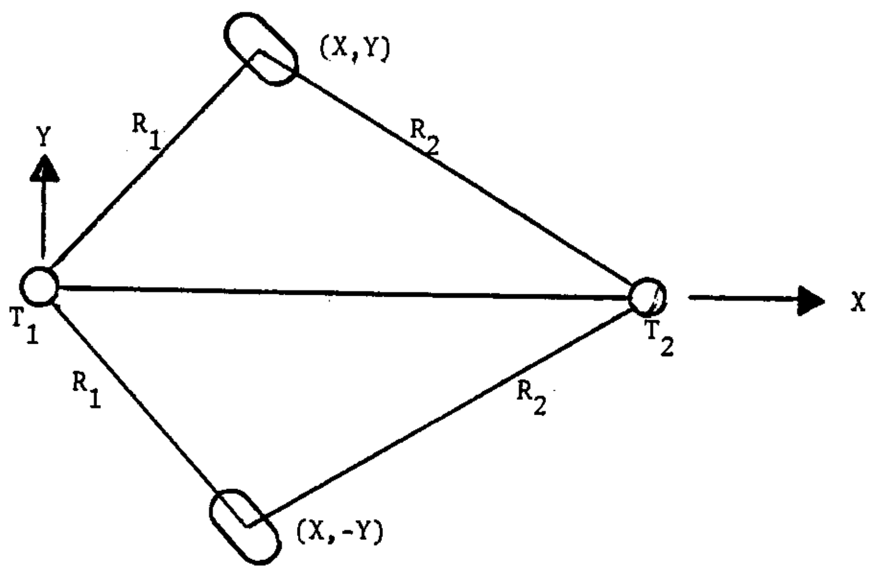


Figure 9. Deterministic Positioning

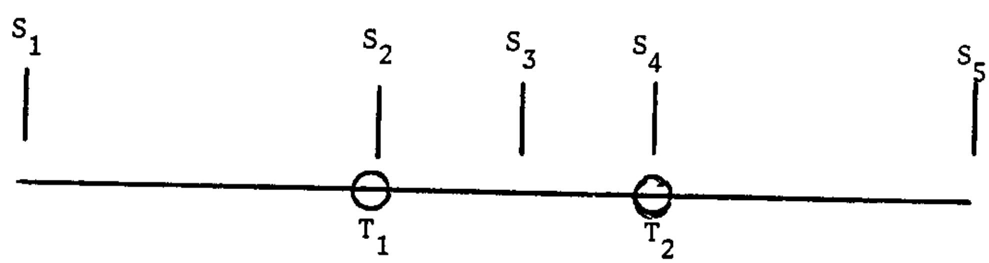


Specifying the ocean model is straightforward and virtually independent of the actual position determination within a computer program. The statistics generated by this method allow flexibility within the program to validate the computed position fix.

A transponder net is not usable for navigation until it is surveyed and the relational parameters are computed. Several techniques and methods are available. The number of transponders and the geometry of the net determine the method of collecting round trip travel times. All computations contain some type of minimization algorithm and produce some statistical data to determine the validity of the survey. Two categories of surveys are used in the field: continuous or one-time. The continuous survey works on the principle that the net is installed, then used for navigation immediately. During navigation, the net is calibrated continuously. Scripps' DEEP TOW uses this category effectively. Its disadvantage is that transponder depths and baseline lengths keep changing, so a clear vehicle track is not directly available.

The second category, the one-time survey, assumes installing a net, surveying the net, calibrating the net, and then navigating within the net. Within this category, three types are discussed here: two-transponder baseline crossing; three-transponder and multiple-(n) transponder surveys. With a two-transponder baseline crossing, five survey points are collected on the transponder baseline. (See Figure 10): one at each end of the baseline at infinity; one on top of each transponder; and one between the two transponders. It is sufficient to say that a

Figure 10. Baseline Crossing Survey



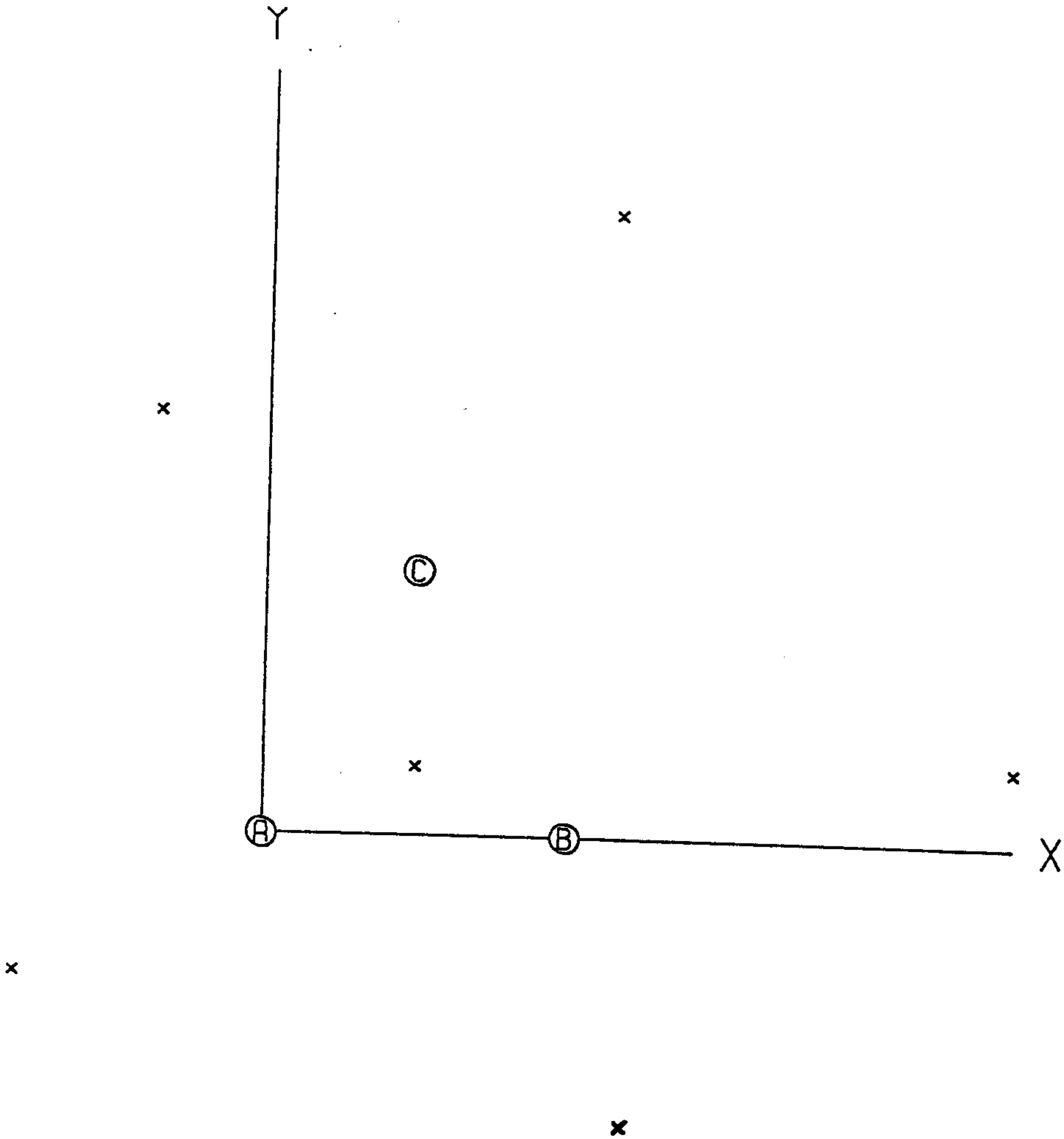
computer program calculates the baseline length and the depths of the two transponders.

The three-transponder survey by a ship, as defined by WHOI's Program SWURV, uses non-linear regression and Fletcher-Powell minimization algorithms to compute the depths and relational parameters. A minimum of six distinct survey points must be collected to estimate the six relational parameters (three depths, baseline length, and X-Y position of the third transponder by assuming the depth of the ship's transducer is a constant). These six survey points must not lie on a conic section (the mathematics of the geometry is unstable). Practically, this can be eliminated by collecting five or more survey points around the outside of the net at an infinite distance and, then, by collecting at least one point inside the net. (See Figure 11) Statistical data are produced by the program so the operator can determine the validity of the survey.

The n-transponder survey by a ship, as defined by WHOI's Program ESTIMEXX, uses non-linear regression mathematics to determine any number of relational parameters. The limitations of the geometry and mathematics of SWURV also apply to this program. That is, there must be at least one survey point collected for each parameter to be estimated and a minimum of six fixed parameters for each program execution (necessary to fix the geometry to eliminate the folding gate phenomenon), and the survey points must not lie on a conic section.

Modeling of the ocean environment within the program is generalized in the attempt to facilitate a much more accurate determination of the estimated parameters. Instead of minimizing

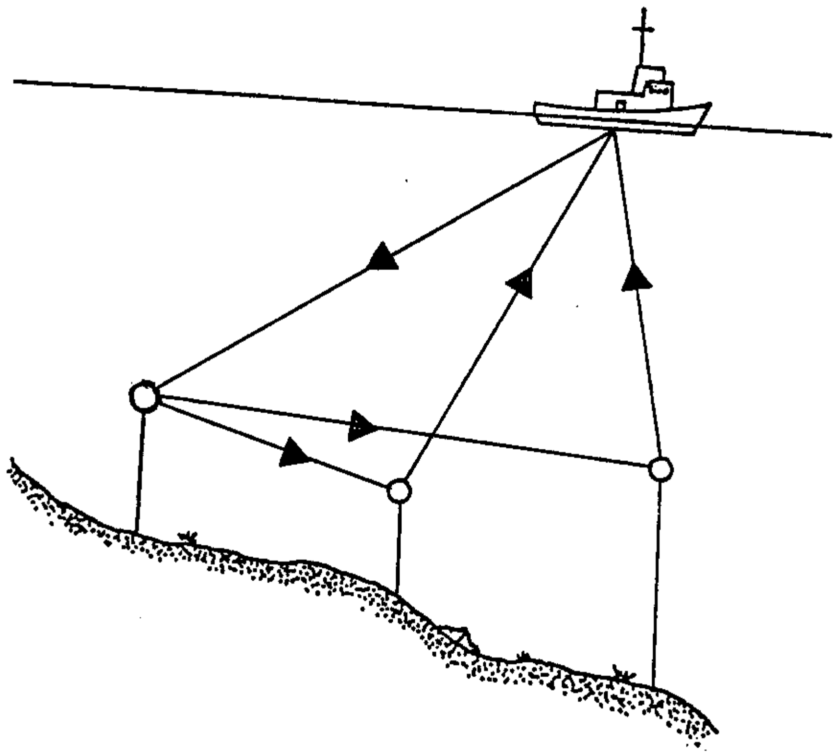
Figure 11. Survey 6



the sum of squares error of slant ranges, ESTIMEXX models the round trip travel times. For instance, the measured travel time for an acoustic pulse that travels from the ship to the transponder and back to the ship is modeled using estimated positions of the ship and transponder. The difference between this computed travel time and the measured travel time is squared and summed with all others. An iterative procedure computes new positions of the ship and transponder and thus new round trip travel times until the sum of squares error is minimized. This technique allows very flexible signaling paths to increase the accuracy of the survey while eliminating the tedious task of computing individual slant ranges from the measured travel times. In other words, the measured travel time is used directly in the matrices and all of the mathematics is in the model of travel time computation.

Program ESTIMEXX was designed to compute the depths and relative positions of the transponders within a net to an accuracy of 12-20 cm instead of the usually accepted 4-5 m. To accomplish this, new signal paths had to be defined and measured (this was done by ATNAV, a product of EG&G, Sea-Link Division). The signal path was dubbed "singaround," and simply used one of the fixed transponders in the same way as WHOI's FISH cycle signaling pattern: ship to singaround transponder, to each other transponder, and back to the ship. (See Figure 12) Each transponder in the net is commandable to operate in either the normal or singaround mode. This signal path allows for an excellent determination of the horizontal spacing of transponders

Figure 12. Singaround Mode of Transponder



and, therefore, a survey resulting in more accurate relational parameters.

Although the techniques presented above describe the navigation of a surface ship, the same techniques are used by a manned submarine. Consequently, there is no reason these techniques cannot be expanded to include the untethered, unmanned submersible. Although there may be limitations and technical deficiencies, a reasonable development effort might overcome them. The case of transponder net survey techniques by a surface ship as presented will require a great deal of thought and development so that an unmanned, untethered, remote vehicle can deploy and survey a transponder net efficiently and accurately.

Figures were taken from the following sources:

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Man-Machine Systems and Their Relationship to Underwater Robotics

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The overall question is: where does man fit into the general area of autonomous, unmanned vehicles? The reason for an "unmanned" vehicle is that it does not jeopardize human life. "Autonomous" is more difficult to define in terms of the degree of autonomy. Between human and computer control are what might be called "control mode tradeoffs." Other issues include force reflection (e.g., joysticks, switches); time delay, if we are using acoustic links; video (frame-rate and resolution and gray scale tradeoffs); tactile (both sensor and display); sonar (how to display it). These all affect control issues.

An important trend is toward supervisory control (i.e., a human talking to a computer and the computer controlling the dynamic vehicle, or manipulator, or process). Here again are issues of command language and teleproprioception (or, what are my limits in space, or how is my remote arm positioned, or where is my manipulator relative to another object.) More general issues include levels of automation, failure detection and identification, isolation and recovery, and workload definition.

If one considers master-slave with force reflection as one most desirable capability, then we at MIT have run through experiments from which numbers or some form of performance quantification has been obtained. If we look at the time it takes to perform a task with any other direct manual control relative to a master-slave with force reflection, then we should get numbers all larger than 1. Such tasks as picking up tools or turning valves by using switches, produces numbers from 3 or 4 to as high as 15 (the ratio between switches to master-slave force reflection). Joysticks are on the order of 5.

We began working with time-delay in the early 60s for NASA to make predictions on how long it takes to perform simple tasks as a function of the "index of difficulty" (a log of the distances we had to move compared to the distance we had to move to within--much like an error tolerance) and the time delay. From this it was revealed that one can make a very good prediction concerning how long it will take to perform a particular task. Stamford Research Institute carried this further by adding to the time-delay experiments the concept of "degrees of constraint." This showed that, as a function of degrees of constraint, one obtained increasing completion times. From this, and from work with various types of predicting devices at MIT and elsewhere, the operator can compensate for the time delay to some extent.

More recent research involved looking at telemanipulation over a very bandwidth-constrained channel to view the object undersea. By degrading the pixels from 128 x 128 and the gray-scale from 4 bits and the frame rate, we addressed this question: could one do manipulative tasks using TV that became much worse. Experiments were set up that, first, trained the operators and then permitted them (once they reached a performance plateau) to conduct the various tasks under varying TV conditions. In one instance, for example, we looked separately at performance as a function of frames/second with pixels and gray scales held constant and, subsequently, varied the other two parameters independently as manipulation tests were performed by the human operator viewing the task over the degraded TV. (See: Ranadive, V. and T. B. Sheridan. 1981. Video Frame-rate, Resolution and Grayscale Tradeoffs for Undersea Telemanipulator Control. Proc. of 1981 Annual Conference on Manual Control.)

Other work involves the supervisory control of a manipulator, in which the basic idea is to increase the capabilities of purely manual control systems through computer intervention. This work is discussed by Yoerger, D. R. and T. B. Sheridan. 1981. Development of a Supervisory Manipulation System for a Free-Swimming Submersible. Proc. IEEE Oceans '81, v. 2, pp. 1170-1174. The reader is referred there for details.

Other questions in the man-machine area are being studied, these include: 1) the desirability of analog or symbolic displays (i.e., spatial isomorphism vs. alpha-numeric); 2) internal models (cognitive models within the control scheme); and 3) application of optimization techniques.

Acoustic Communication

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An acoustic link developed within the Ocean Technology Department, Advanced Systems Division, of NOSC, has successfully demonstrated high-speed telemetry of digital data from ocean depths of almost three miles. During tests in June 1981, the acoustic link telemetered continuous 4,800 bits/second digital data from 15,000-foot depths.

During the tests held in the Pacific Ocean, 400 nautical miles northwest of San Diego, a near-bottom instrumentation package telemetered 10 million bits of pseudo-random digital data to a surface platform with a total of 10 received errors, for an average bit error rate of 1×10^{-6}. These results were obtained as the surface platform drifted from a position directly over the instrumentation package to an offset angle greater than 45^{o} from the vertical. Under the same conditions, 2.6 million bits of data were transmitted to the instrumentation package at a data rate of 1,200 bits/second, without a single error.

During a two-week cruise on the Paul Langevin III, operated on a contract with Tracor, Inc., testing commenced at 100 feet, went to 4,000 feet at San Clemente Island, then went to deeper waters for tests at 12,000 and, finally, 15,000 feet. The objective of the test was to verify the design of a high data rate acoustic link operable from depths of 2,000 to 20,000 feet. This is the design depth of the free-swimming vehicle being developed for the Navy's Advanced Unmanned Search System (AUSS) program, the acoustic link will provide the sole communication link between the AUSS vehicle and the surface.

In addition to the digital data, transmitted voice, pings, cw tones and slow-scan television were also transmitted during the tests. All transmissions were at a transducer input power level of 33 watts, and were between 8 and 14 kilohertz.

Data gathered during the tests indicate that the acoustic link will be operable to depths of 20,000 feet by increasing the power to approximately 60 watts.

The modulation technique used was dual independent sideband with an injected pilot tone to provide for doppler correction. Within each independent sideband, the pseudo-random digital data were transmitted using quad differential phase shift keying, and slow-scan television data was transmitted using non-orthogonal frequency shift keying.

The NOSC Benthic Untethered Multipurpose Platform (BUMP) was used throughout the tests as an acoustic source and receiver. BUMP is a pop-up instrumentation package weighing 1,000 pounds and measuring 30" x 30" x 72". It is launched from a surface ship and sinks to the bottom for data transmission and reception. After a predetermined time period on the bottom, or upon acoustic command, BUMP jettisons enough ballast to make itself positively buoyant with its syntactic foam flotation and rises to the surface for recovery.

The June tests culminated a five-year effort begun by Dr. Alan Gordon of NOSC with IR/IED funding to determine limitations on high data rate telemetry imposed by the near vertical (approximately 0 to 45 degrees) acoustic channel. In addition to

AUSS, the link has a number of other potential applications, including seismic monitoring; dump site monitoring; control and communications for unmanned, untethered vehicles; submarine communications and surveillance.

Microcomputers

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The Marine Systems Engineering Laboratory (MSEL) has recently conducted studies of existing microprocessor systems to determine, as precisely as possible, which devices are superior and what percentage of their capabilities can be used in underwater autonomous vehicles. A comparison of various microprocessors is shown in Table 1. These salient features of all systems must be addressed:

1) The microprocessor itself and what is actually available

2) What memory is available; and what will be available

3) What development systems for microcomputer softwareare available and, which of these are available for use.

Our choice, after pursuing this study, was the recently developed Motorola 68000. One of the most desirable features of this device is that it has reached the stage where equipment that will allow development of programs can be obtained. Also, the hardware is available to support and maintain it. MSEL's system has been together for three months and the hardware has been available for about six months.

Bubble memory is a reality, but many questions remain to be resolved. This type of memory shows great promise for autonomous vehicles, since it operates like a reliable floppy disk without moving parts. Although we now have a bubble memory recorder, all the software has yet to be developed to permit full use of its capabilities. This system should be in our vehicle (EAVE EAST) within six-to-eight months. We have recently purchased a develop-

Table 1

Comparison of 68000 to Some Other Processors

	68000	PDP 11/40	LS1-11	8086	6100 (PDP-8)
Direct Memory Space	16 MByte	65 KByte	65 KByte	1 MByte	4K x 12
CPU Registers	17 - 32 bit	7 - 16 bit	7-16 bit	17 - 16 bit	2-12 bit
Hardware MPY/Divide	signed/ unsigned	signed	signed	signed/ unsigned	no
32 Bit Arithmetic	yes	no	no	no	no
Addressing Modes	12	12	12	8	3
Stack Oriented	yes	yes	yes	yes	no
Execution Time	@ 8MHz				
R to R move	0.5μs	0.9μs	3.5μs	0.4μs	2.5μs
Memory to R	1.5μs	2.25μs	7.0μs	2.8μs	2.5μs
Indirect	1.0μs	1.88μs	4.9μs	2.6μs	3.75μs
Indexed	1.5μs	2.50μs	4.9μs	4.0μs	
CPU Power	1.2W		19W	1.2W	.02W

ment system using FORTH, PASCAL and C from Empirical Research. It is due for delivery in November.

A paper delivered at OCEANS 81 that further expands on the subject of the microprocessor computer in the autonomous vehicle is included in the Appendix to this volume.

MSEL has partitioned its system into multiple processors to ease the transition from earlier developments into the current program. A second reason for this is to communicate from, for example, the CPU which runs the thrusters to the central command CPU through a serial link. On occasion some of the pieces end up in different pressure vessels and communication between them through a parallel bus is very costly. Our system is made such that consistant pieces are partitioned off, each having sufficient intelligence to perform bounded tasks, for example, to supply thrust commands and produce signals to activate the motors. A faulty piece can be separated and debugged until it is working properly using a terminal or laboratory computer. We will eventually define a communication CPU.

The navigation CPU is presently a 6100, but much of the intelligence in it will subsequently migrate to the 68000 by changing the hierarchical level of the data concepts that are transferred from one CPU to the other.

We have recognized that, as we get into more complex programs, more intellignce will be needed in the central CPU. We have gone to a 16/32-machine for two reasons: 1) the ever-increasing complexity of navigation and motion control equations and 2) much of the mathematics can be done as single-precision arithmetic. After reviewing the processors available we decided on the 68000 owing to its following characteristics:

- 32-bit arithmetic in a 16-bit architecture
- Similarities to PDP-11 architecture
- Higher-level language concepts
- Powerful exception handling
- Asynchronus bus timing
  - --multiple processor configurations
  - --interface with very low power memory

Features of the 68000 CPU which we employ include the following:

- Direct addressing of 16 MBytes of memory
- Eight 32-bit data registers
- Nine 32-bit address registers
- BYTE, Word, Long Word Operation
- 32-bit Multiply/Divide
- Multi-Task Hardware
- Asynchronous Bus Structure (can use with CMOS)
- Supports Higher-Level Constructs (Link/Unlink)
- Relatively Low Power
- Multiple Manufacturers (5)
- Whitesmith's C and PASCAL Available

MSEL's 68000 Design Goals

- Stand-alone CPU/UART/monitor card
- Buffered interrupt driven I/O on all ports
- Identification of all error exceptions
- Full bus implementation for future expansion
- CMOS where possible to reduce power

The configuration of the Command Computer System so far implemented in the vehicle is shown in Figure 1.

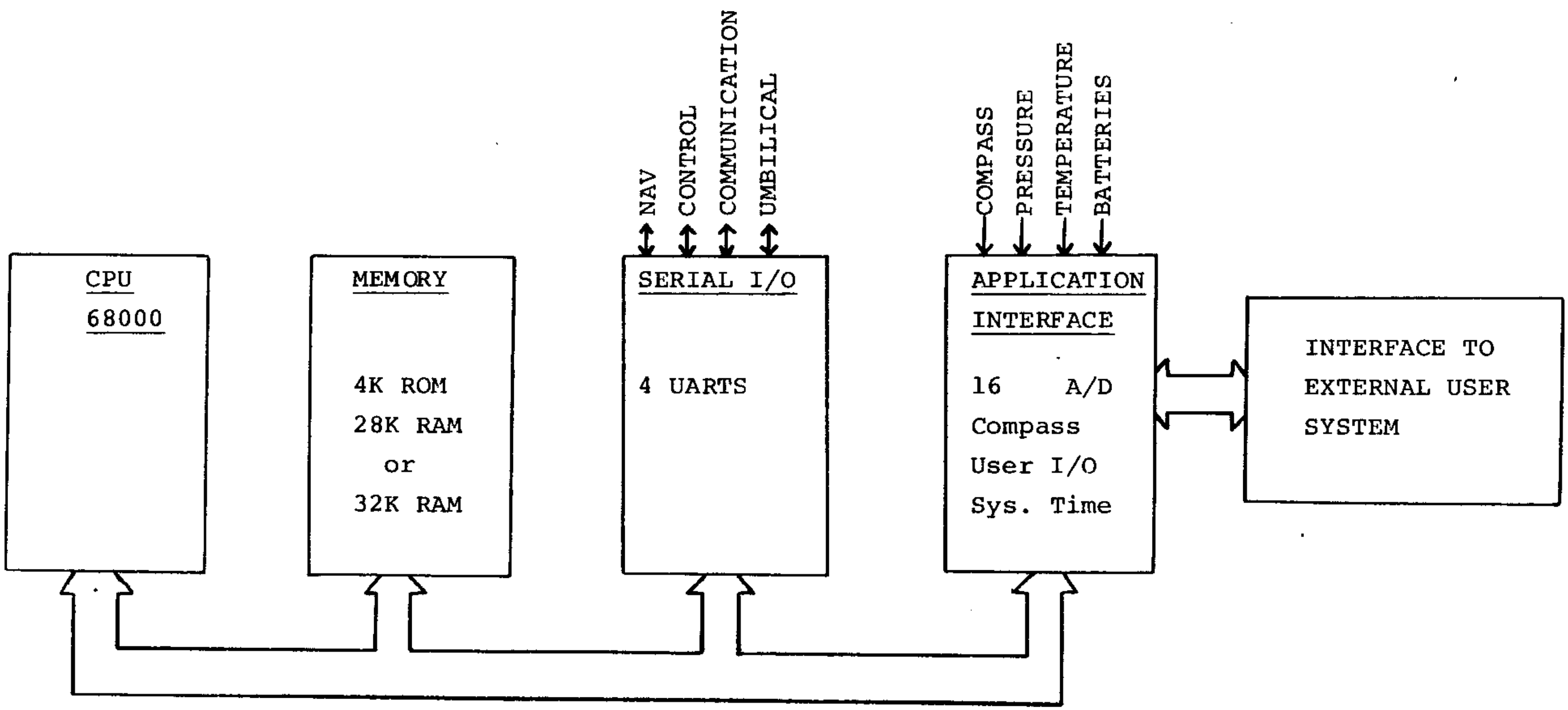
Current Card Capabilities

- 68000 CPU
- 32K Byte CMOS RAM
- Four port CMOS UART's
- Application: pressure, compass, temperature, batteries

Future Card Capabilities

- Power-down CMOS RAM card
- Multi-port RAM
- CCD camera frame grabber
- Mass storage interface

Figure 1. Command Computer System



Charles S. Draper Laboratories Activities

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Draper Labs has been working in the remotely operated vehicle field for the past year. Since we have had many years experience in design of manned vehicles for the Navy and NOAA, we felt that by bringing together the many unique capabilities of the Lab we might be able to provide an insight into solving some of the problems of autonomous ROVs.

The program objective was to provide an alternative to divers and tethered ROVs for tasks that do not require "hands on" human control. One of the first steps was to gather and assess available research and development results worldwide. Several other goals were to: 1) define needed technologies for advanced missions where man cannot be present; 2) identify technology gaps blocking creation of such systems; and 3) generate design methods and capabilities.

Some of the readily identifiable needed technologies were: autonomous work vehicles; long-range high data density communications; high accuracy homing methods; long-duration, high density energy storage; navigation, environmental sensors; and supervisory control (periodic updates on vehicle status).

To approach this study we defined a family of missions that taxed ROV technologies. In this respect, we arbitrarily assigned missions, defined mission scenarios and power energy profiles, and laid out vehicle configurations. Although there were simple solutions to many of these problems, we forced our thinking to concentrate on alternative means.

Eight missions were defined:

1) Short range, payload (500 lbs) work mission
2) Area survey
3) Object recovery mission
4) Medium range, large object placement
5) Trenching
6) High-speed decoy
7) Platform inspection
8) Inspection/retrieval at waste disposal sites

The various disciplines that go into these designs include microprocessors, energy/power, acoustics, sensors, work functions, vehicle configurations, controls, hydrodynamics, navigation and reliability. The outputs of the study were designs for a variety of different vehicles that included preliminary vehicle specification, characteristics, equipment list, work systems, and a report detailing the capabilities of the vehicle based on current state of technology with conclusions and recommendations. Definition of specific technologies and of areas for possible advances where Draper Labs could concentrate their efforts were also addressed.

Critical technologies that came out of these studies were: supervisory control acoustic communications (transmission delays, multipath, high frequency attenuation problems), and navigation and positioning (to close with the work object). Several potential solutions to these problem areas have been identified. One, in particular, was to include tactile sensors on a manipulator to obtain a high degree of positional accuracy for work systems.

Control Systems

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When dealing with vehicle design, we try to fit distances and time into some framework and derive a mission scenario (the way we will do certain tasks). For vehicles of 30 ft (LOA) and more, we speak of control within 1 or 2 feet after which the vehicle's work system package takes over and provides control to within inches. Within the 1 cm to mm range, some type of device (e.g., cone or jig) must be arranged that can do the tasks requiring these very fine motions.

The general navigation sensors (surface-deployed) permit work within the 100 m range; bottom-deployed transponders provide tens of meters of range. Below this we move to an array of transponders or employ visual sighting. For each individual program we must address the question: what will we use in the various distance regimes. (Figure 1). The same approach must be used in time regimes. (Figure 2).

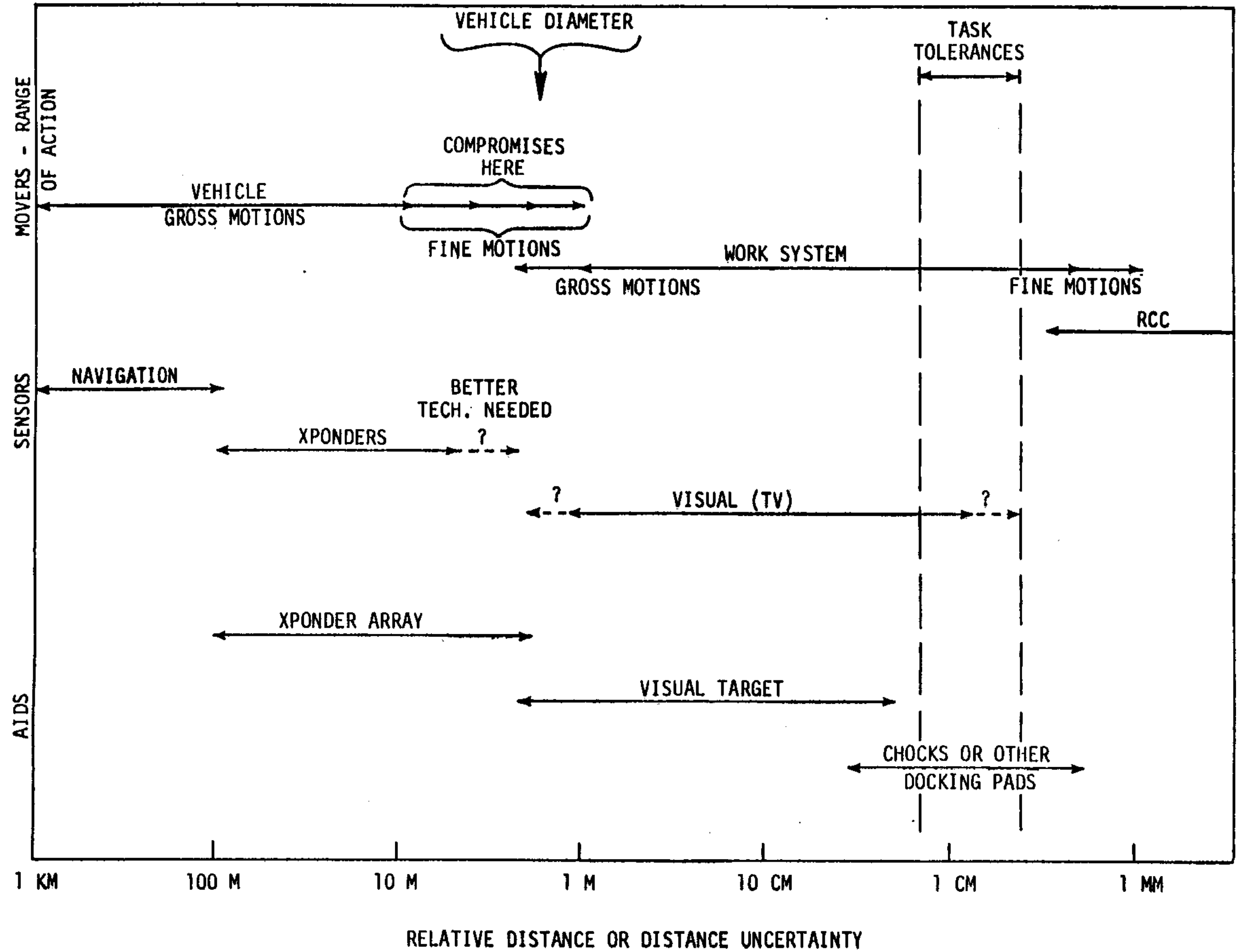
When we set up the vehicle and its control system we have to provide a synthesis of control, which usually starts with a set of equations describing the vehicle, the degrees of freedom in the general case and for the sensor and actuator dynamics.

The state of the vehicle in the vertical and horizontal planes and its dynamic susbystems (sensors) are described by state vectors x, components of which are:

Vertical Plane

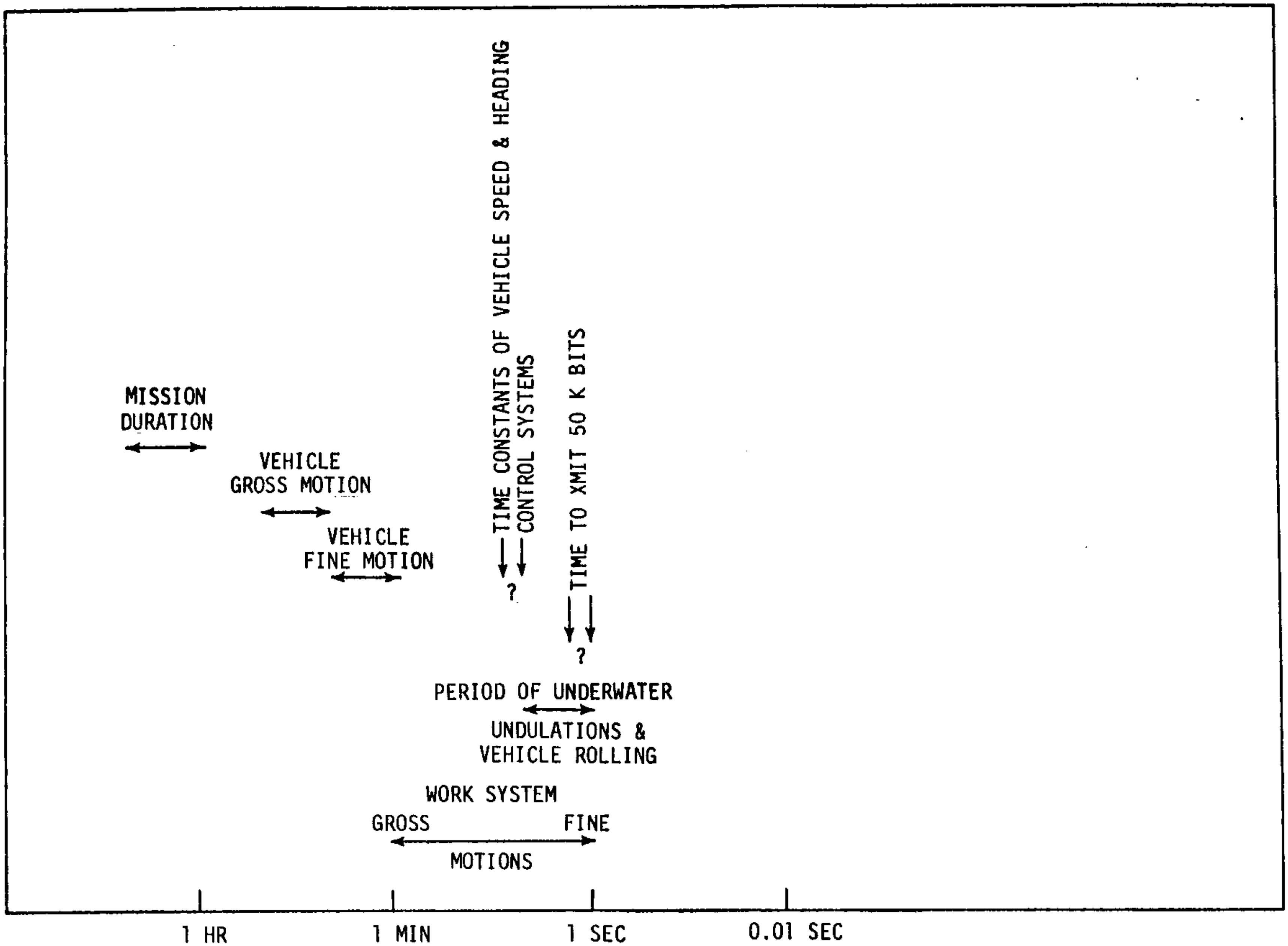
$\Delta\mu$	Change of forward velocity
w	Velocity of origin down in vehicle coordinates
q	Pitch rate, bow up is positive
θ	Pitch angle, bow up is positive
z_0	Depth of origin relative to desired depth

Figure 1



MOVERS - RANGE OF ACTION
SENSORS
AIDS
VEHICLE DIAMETER
TASK TOLERANCES
COMPROMISES HERE
VEHICLE GROSS MOTIONS
FINE MOTIONS
WORK SYSTEM
GROSS MOTIONS
FINE MOTIONS
RCC
NAVIGATION
BETTER TECH. NEEDED
XPONDERS
?
?
VISUAL (TV)
?
XPONDER ARRAY
VISUAL TARGET
CHOCKS OR OTHER DOCKING PADS
1 KM
100 M
10 M
1 M
10 CM
1 CM
1 MM
RELATIVE DISTANCE OR DISTANCE UNCERTAINTY

Figure 2



MISSION DURATION
VEHICLE GROSS MOTION
VEHICLE FINE MOTION
TIME CONSTANTS OF VEHICLE SPEED & HEADING
CONTROL SYSTEMS
?
TIME TO XMIT 50 K BITS
?
PERIOD OF UNDERWATER UNDULATIONS & VEHICLE ROLLING
WORK SYSTEM
GROSS
FINE
MOTIONS
1 HR
1 MIN
1 SEC
0.01 SEC

q_s	Pitch rate as measured by sensor
θ_s	Pitch angle as measured by sensor
δ_s	Stern plane angle

Horizontal Plane

v	Sway velocity, positive to starboard
r	Yaw rate, positive clockwise looking down
ρ	Roll rate, positive clockwise looking forward
ϕ	Roll angle, positive roll to starboard
Ψ	Heading direction relative to desired heading
ρ_s	Measured roll rate from sensor
ϕ_s	Measured roll angle from sensor
δ_r	Rudder angle

What we are looking for is a control algorithm that performs the task we want, for example, accurate maneuvering or minimizing power/energy. So, some weighting analysis must be performed to determine what the vehicle is going to be allowed to do; what motions will be permitted; and how much effort will be put into control.

Problems

1) Measuring derivatives--either analytically or by testing. The analytical approach can be accurate to within 10% in some easy terms or by a factor of 3 in more complex terms. For highest accuracy, we are forced to go with some form of experimentation or testing.

2) Observability of unmeasured state variables. Terms within the equations of motion, such as sideways velocity, are not normally available (e.g., sensors that can measure sideways velocity).

3) Noise & sensors

4) Non-linear terms

5) Time history dependence owing to change of vehicle's environment (vortex shedding). At times, the second order

differential equation description of the vehicle breaks down because water is not a perfect fluid. For example, lift on a submarine sail also produces trailing vortices, such as in the wake of a propeller. Consequently, there is a change in the operating environment. So, standard Naval architect formulations are no longer applicable.

If the vehicle is proceeding nearly straight ahead, linear models are accurate. But the effects of the vortex system, however, can be large. Linear models are particularly difficult to justify when the vehicle is hovering, mating, or working at very low speeds. One example of the breakdown of this approach can be seen when a military submarine is proceeding at constant depth and speed, and the rudder is turned. It might turn out that motions in more than just the horizontal plane result, the submarine might also try to surface or to dive. There are coupling terms in the non-linear equations of motion that relate side velocity and turning rate to pitch and heave forces. The problem is to measure these coefficients and determine what hydrodynamic mechanisms are causing this to happen. Such measurements and determinations are possible and it can be shown that, under certain conditions, there will be a net force exerted downward on the deck owing to sail vortex image and sideslip velocity. The pitch and heave inputs depend upon how far the rudder was turned and for what duration. These forces are impossible to study in a towing tank since there are no 3-dimensional towing tanks available that permit generation of forces owing to complicated trajectories. One solution to this problem is the Naval Control Systems Center's ASCOP which will permit measurements of radical forces in 3-dimensions by using the ocean itself as a test tank.

The following equations of motion are taken from the work accomplished at the Naval Ship Research and Development Center (NSRDC).

7.3.2 Control Input

The control vector $\vec{u}$ has component δ_{sc} in the vertical plane where δ_{sc} is the commanded stern plane angle. In the horizontal plane the component is δ_{nc}, the commanded rudder angle. These commanded angles are obtained by a matrix multiplication $\vec{u} = G\vec{x}$ where G is a constant matrix of gains. The purpose of the synthesis is to obtain optimum values of these gains in the horizontal and vertical planes.

The control synthesis will be done by solving the optimal regulator problem. The vehicle state equation is expressed in the form:

$$\dot{\vec{x}} = A\,\vec{x} + B\,\vec{u}$$

from a linearization of the equations of motion in the vertical and horizontal planes. The object is to minimize a cost function representative of a combination of motion variables and control actuation of the form:

$$J = \int_0^\infty (x^t\, Q\, \vec{x} + \vec{u}^t\, R\, \vec{u})\, dt$$

The diagonal matrices Q and R are set up to meet requirements for adequate stability and control. The elements in the matrix Q weight the motions of the corresponding variables in the state vector. The elements of the matrix R weight motions of the control surfaces. The minimization solution leads to a gain matrix G where:

$$\vec{u} = G\,\vec{x}$$

This is a pure proportional control solution in the continuous time domain. It is assumed that the control will be digitized and solved on an on-board microcomputer for output to control devices such as stepper motors or a servomotor with position feedback. This may be modelled by first order systems in the set of equations of motion. The dynamics of the sensors must also be included in the set of equations of motion. The pendulum type sensors anticipated for roll and pitch measurement can be modelled as second order systems in the equations of motion relating actual to measured angles. Natural frequencies for these sensors are about three Hertz which may be enough above vehicle eigenvalues to eliminate these equations after testing the effects.

7.4. Linearized Equations of Motion

7.4.1 Vehicle Equations

The linearized equations of motion that will be used for control synthesis are:

Vertical Plane

Surge: $(m - X\dot{u})\Delta\dot{u} - Xu\Delta u + mZ_G\dot{q} = 0$

Heave: $(m - Z\dot{w})\dot{w} - (mu_o + Z_q)q - ZwW - Z\dot{q}\,\dot{q} = Z\delta_s\delta s$

Pitch: $mZ_G\Delta\dot{u} - M_{\dot{w}}\dot{w} - MwW + (I_y - M\dot{q})\dot{q} - M_q q - M_\theta\theta = M_{\delta s}\delta s$

Horizontal Plane

Sway: $(m - Y_{\dot{v}})\mathring{v} - Y_v v - Y_r\mathring{r} + (mU_o - Y_r)\,r - mZ_G p = Y_{\delta r}\delta r$

Roll: $-mZ_G v - mZ_G r + (I_x - K_{\mathring{p}})\mathring{p} - K_p p - K_\phi\phi = K_{\delta r}\delta r$

Yaw: $-N_{\dot{v}}\mathring{v} - N_v v + (I_Z - N_{\dot{r}})\dot{r} - N_r r = N_{\delta r}\delta r$

In these equations standard Society of Naval Architects and Marine Engineers notation is used. The constants in the equations represent the vehicle characteristics:

m mass of vehicle with water in free flooding spaces

$X_{\dot{u}}$ derivative of axial force with surge acceleration

X_u derivative of axial force with forward speed

Z_G position of center of gravity below origin

$Z_{\dot{w}}$ derivative of downward force with downward acceleration

u_o equilibrium forward speed

Z_q derivative of downward force with pitch rate

Z_w derivative of downward force with downward velocity

$Z_{\delta s}$ derivative of downward force with stern plane angle

M_w derivative of pitch moment with downward acceleration

$M_{\dot{w}}$ derivative of pitch moment with downward velocity

I_y moment of inertia in pitch about origin

$M_{\dot{q}}$ derivative of pitch moment with pitch acceleration

$Z_{\dot{q}}$ derivative of downward force with pitch acceleration

M_q derivative of pitch moment with pitch velocity

M_θ derivative of pitch moment with pitch angle

$M_{\delta s}$ derivative of pitch moment with stern plane angle

$Y_{\dot{v}}$ derivative of sway force with sway acceleration

Y_v derivative of sway force with sway velocity

$Y_{\dot{r}}$ derivative of sway force with yaw acceleration

Y_r derivative of sway force with yaw rate

$Y_{\delta r}$ derivative of sway force with rudder angle

I_x roll moment of inertia

$K_{\dot{p}}$ derivative of roll moment with roll acceleration

K_p derivative of roll moment with roll rate

K_ϕ derivative of roll moment with roll angle

$K_{\delta r}$ derivative of roll moment with rudder angle

$N_{\dot{v}}$ derivative of yaw moment with sway acceleration

N_v derivative of yaw moment with sway velocity

I_z yaw moment of inertia about origin

$N\dot{r}$ derivative of yaw moment with yaw acceleration

Nr derivative of yaw moment with yaw rate

$N_{\delta r}$ derivative of yaw moment with rudder angle

7.4.2 Control Surface Dynamics

The rudders and stabilizing fins are modelled by first order equations added to the vehicle equations of motion. For example, in pitch:

$$\delta_s + \tau_f \delta s = \delta_{sc}$$

where δ_s is the position of the fin, τ_f is the time constant of the control actuator lag and δ_{sc} is the commanded fin position.

7.4.3 Sensor Dynamics

The roll and pitch sensors are modelled as damped pendulums and, for example, the pitch sensor equation is:

$$q_s + 2\xi_\theta w_\theta qs + w^2{}_\theta \theta s = w^2{}_\theta \theta$$

where q_s is the measured pitch rate and θ_s is measured pitch angle. ξ_θ and w_θ are the damping and natural frequency of the sensor. It is likely, as the design progresses, that these equations may be dropped and the actual pitch and roll angles set equal to the measured ones. However, this assumption cannot be made initially.

The equations are presented in the following order: axial force, lateral force, normal force, rolling moment, pitching moment, and yawing moment. In addition certain kinematic relations are given.

AXIAL FORCE

$$m[\dot{u} - vr + wq - x_G(q^2 + r^2) + y_G\ (pq - \dot{r}) + z_G\ (pr + \dot{q})] =$$

$$+ \frac{\rho}{2}\,\ell^4[X_{qq}'\ q^2 + X_{rr}'\ r^2 + X_{rp}'\ rp]$$

$$+ \frac{\rho}{2}\,\ell^3[X_{\dot{u}}'\ \dot{u} + X_{vr}'\ vr + X_{wq}'\ wq]$$

$$+ \frac{\rho}{2}\,\ell^2[X_{uu}'\ u^2 + X_{vv}'\ v^2 + X_{ww}'\ w^2]$$

$$+ \frac{\rho}{2}\,\ell^2 u^2\ [X_{\delta r\ \delta r}'\ \delta r^2 + X_{\delta s\ \delta s}'\ \delta s^2 + X_{\delta b\ \delta b}'\ \delta b^2]$$

$$+ \frac{1}{2}\,\rho\ell^2[a_i\ u^2 + b_i\ uu_c + c_i\ u_c{}^2]$$

$$- (W - B)\sin\theta$$

$$+ \frac{\rho}{2}\,\ell^2[X_{vv\eta}'\ v^2 + X_{ww\eta}'\ w^2 + X_{\delta r\ \delta r\eta}'\ \delta_r{}^2\ u^2$$

$$+ X_{\delta s\ \delta s\eta}\ \delta_s{}^2\ u^2](\eta-1)$$

LATERAL FORCE

$$m[\dot{v} - wp + ur - y_G (r^2 + p^2) + z_G (qr - \dot{p}) + x_G (qp + \dot{r})] =$$

$$+ \frac{\rho}{2} \ell^4 [Y_{\dot{r}}' \dot{r} + Y_{\dot{p}}' \dot{p} + Y_{P|P|}' P|P| + Y_{pq}' pq + Y_{qr}' qr]$$

$$+ \frac{\rho}{2} \ell^3 [Y_{\dot{v}}' \dot{v} + Y_{vq}' vq + Y_{wp}' wp + Y_{wr}' wr]$$

$$+ \frac{\rho}{2} \ell^3 [Y_r' ur + Y_p' up + Y_{|r|\delta r}' u|r|\delta r + Y_{v|r|}' \frac{v}{|v|} |(v^2 + w^2)^{\frac{1}{2}}| |r|]$$

$$+ \frac{\rho}{2} \ell^2 [Y_*' u^2 + Y_v' uv + Y_{v|v|}' v |(v^2 + w^2)^{\frac{1}{2}}|]$$

$$+ \frac{\rho}{2} \ell^2 [Y_{vw}' vw + Y_{\delta r}' u^2 \delta r]$$

$$+ (W - B) \cos \theta \sin \phi$$

$$+ \frac{\rho}{2} \ell^3 Y_{r\eta}' ur (\eta - 1)$$

$$+ \frac{\rho}{2} \ell^2 [Y_{v\eta}' uv + Y_{v|v|\eta}' v|(V^2 + w^2)^{\frac{1}{2}}| + Y_{\delta r\eta}' \delta_r u^2](\eta - 1)$$

NORMAL FORCE

$$m[\dot{w} - uq + vp]$$

$$= + \frac{\rho}{2} \ell^4[Z_q{}' \, q + Z_{pp}{}' \, p^2 + Z_{rr}{}' \, r^2 + Z_{rp}{}' \, rp]$$

$$+ \frac{\rho}{2} \ell^3[Z_{\dot{w}}{}' \, \dot{w} + Z_{vr}{}' \, vr + Z_{vp}{}' \, vp]$$

$$+ \frac{\rho}{2} \ell^3[Z_q{}' \, uq + Z_{|q|\delta s}{}' \, u|q|\delta s + Z_{w|q|}{}' \, \frac{w}{|w|} \, |(v^2 + w^2)^{\frac{1}{2}}||q|]$$

$$+ \frac{\rho}{2} \ell^2[Z_*{}' \, u^2 + Z_w{}' \, uw + Z_{w|w|}{}' \, w|(v^2 + w^2)^{\frac{1}{2}}|]$$

$$+ \frac{\rho}{2} \ell^2[Z_{|w|}{}' \, u|w| + Z_{ww}{}' \, |w \, (v^2 + w^2)^{\frac{1}{2}}|]$$

$$+ \frac{\rho}{2} \ell^2[Z_{vv}{}' \, v^2 + Z_{\delta s}{}' \, u^2 \, \delta s + Z_{\delta b}{}' \, u^2 \, \delta b]$$

$$+ (W - B) \cos \theta \cos \phi$$

$$+ \frac{\rho}{2} \ell^3 \, Z_{q\eta}{}' \, uq \, (\eta-1)$$

$$+ \frac{\rho}{2} \ell^2[Z_{w\eta}{}' \, uw + Z_{w|w|\eta}{}' \, w|(v^2 + w^2)^{\frac{1}{2}}| + Z_{\delta s\eta}{}' \delta_s u^2](\eta-1)$$

ROLLING MOMENT

$$I_x \dot{p} + (I_z - I_y)\, qr\, (\dot{r} + pq)\, I_{xz} + (r^2 - q^2)\, I_{yz} + (pr - \dot{q})\, I_{xy}$$

$$+ m\, [y_G\, (\dot{w} - uq + vp) - z_G\, (\dot{v} - wp + ur)] =$$

$$+ \frac{\rho}{2}\, \ell^5 [K_{\dot{p}}'\, \dot{p} + K_{\dot{r}}'\, \dot{r} + K_{qr}'\, qr + K_{pq}'\, pq + K_{p|p|}' p|p|]$$

$$+ \frac{\rho}{2}\, \ell^4 [K_p'\, u + K_r'\, ur + K_{\dot{v}}'\, \dot{v}]$$

$$+ \frac{\rho}{2}\, \ell^4 [K_{vq}'\, vq + K_{wp}'\, wp + K_{wr}'\, wr]$$

$$+ \frac{\rho}{2}\, \ell^3 [K_*'\, u^2 + K_v'\, uv + K_{v|v|}'\, v|(v^2 + w^2)^{\frac{1}{2}}|]$$

$$+ \frac{\rho}{2}\, \ell^3 [K_{vw}' vw| K_{\delta r}'\, u^2\, \delta r]$$

$$+ (y_G\, W - y_B\, B) \cos\theta \cos\phi - (z_G W - z_B B) \cos\theta \sin\phi]$$

$$+ \frac{\rho}{2}\, \ell^3\, K_{*_\eta}'\, u^2 (\eta - 1)$$

PITCHING MOMENT

$$I_y \dot{q} + (I_x - I_z) rp - (\dot{p} + qr) I_{xy} + (p^2 - r^2) I_{zx} + (qp - \dot{r}) I_{yz}$$

$$+ m [z_G (\dot{u} - vr + wq) - x_G (\dot{w} - uq + vp)] =$$

$$+ \frac{\rho}{2} \ell^5 [M_q{}' \dot{q} + M_{pp}{}' p^2 + M_{rr}{}' r^2 + M_{rp}{}' rp + M_{q|q|}{}' q|q|]$$

$$+ \frac{\rho}{2} \ell^4 [M_{\dot{w}}{}' \dot{w} + M_{vr}{}' vr + M_{vp}{}' vp]$$

$$+ \frac{\rho}{2} \ell^4 [M_q{}' uq + M_{|q|\delta s}{}' u|q|\delta s + M_{|w|q}{}' |(v^2 + w^2)^{\frac{1}{2}}|q]$$

$$+ \frac{\rho}{2} \ell^3 [M_*{}' u^2 + M_w{}' uw + M_{w|w|}{}' w |(v^2 + w^2)^{\frac{1}{2}}|]$$

$$+ \frac{\rho}{2} \ell^3 [M_{|w|}{}' u|w| + M_{ww}{}' |w (v^2 + w^2)^{\frac{1}{2}}|]$$

$$+ \frac{\rho}{2} \ell^3 [M_{vv}{}' v^2 + M_{\delta s}{}' u^2 \delta s + M_{\delta b}{}' u^2 \delta b]$$

$$- (x_G W - x_B B) \cos\theta \cos\phi - (z_G W - z_B B) \sin\theta$$

$$+ \frac{\rho}{2} \ell^4 M_{qn}{}' uq (n-1)$$

$$+ \frac{\rho}{2} \ell^3 [M_{wn}{}' uw + M_{w|w|n}{}' w|(v^2 + w^2)^{\frac{1}{2}}| + M_{\delta sn}{}' \delta_s u^2](n-1)$$

YAWING MOMENT

$$I_z \dot{r} + (I_y - I_x)\, pq - (\dot{q} + rp)\, I_{yz} + (q^2 - p^2)\, I_{xy} + (rq - \dot{p})\, I_{zx}$$

$$+ m\, [x_G\, (\dot{V} - wp + ur) - y_G\, (\dot{u} - vr + wq)] =$$

$$+ \frac{\rho}{2}\, \ell^5 [N_{\dot{r}}'\, \dot{r} + N_{\dot{p}}'\, \dot{p} + N_{pq}'\, pq + N_{qr}'\, qr + N_{r|r|}' r|r|]$$

$$+ \frac{\rho}{2}\, \ell^4 [N_{\dot{v}}'\, \dot{v} + N_{wr}'\, wr + N_{wp}'\, wp + N_{vq}'\, vq]$$

$$+ \frac{\rho}{2}\, \ell^4 [N_p'\, up + N_r'\, ur + N_{|r|\delta r}'\, u|r|\delta r + N_{|v|r}'\, |(v^2 + w^2)^{\frac{1}{2}}|r]$$

$$+ \frac{\rho}{2}\, \ell^3 [N_*'\, u^2 + N_v'\, uv + N_{v|v|}'\, v\, |(v^2 + w^2)^{\frac{1}{2}}|]$$

$$+ \frac{\rho}{2}\, \ell^3 [N_{vw}'\, vw + N_{\delta r}'\, u^2 \delta r]$$

$$+ (x_G\, W - x_B B) \cos\theta \sin\phi + (y_G\, W - y_B B) \sin\theta$$

$$+ \frac{\rho}{2}\, \ell^4\, N_{r\eta}'\, ur\, (\eta - 1)$$

$$+ \frac{\rho}{2}\, \ell^3 [N_{v\eta}'\, uv + N_{v|v|\eta}'\, v\, |(v^2 + w^2)^{\frac{1}{2}}| + N_{\delta r\eta}'\, \delta_r\, u^2](\eta - 1)$$

Deep Ocean Applications

Victor Anderson
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The Marine Physics Laboratory's (MPL) experience to date has been in the areas of cabled vehicles and manned submersibles; not in the area of autonomous vehicles. However, aspects of these cabled vehicles have relevance to autonomous vehicles and, perhaps, would be of value to those who are working in the unmanned, untethered vehicle field. Accordingly, this presentation will consist mainly of a description of these cabled vehicles followed by a brief conjecture as to possible application in autonomous vehicles.

MPL's Cabled Vehicles

MPL has worked with three vehicles: DEEP TOW (a deeply towed fish); RUM (Remote Underwater Manipulator--a tracked vehicle); and ADA (an acoustic detection array). More specific characteristics of these vehicles and devices are given below.

DEEP TOW. This vehicle has been in existence for well over 15 years and probably has more bottom time than any vehicle in its class. The towing cable is an armored coax (RG8U, essentially) that transmits about one kw power down along with multiplexed down going and upcoming telemetring data. The main power consumption is for the strobe light; the rest of the electronics consume minimal power. Instrumentation and attachments that have been and are used on DEEP TOW include the following:

--upward looking echo-sounder (for monitoring vehicle depth);
--suspended particle filter (to collect biological life above the sea bottom);

--nephelometer (for light scattering measurements);
--obstacle avoidance sonar;
--differential pressure gage (to control vehicle height above the bottom);
--downward looking echo-sounder (for high resolution topographic profiling -2° beam width);
--precision depth guage (for absolute pressure/depth);
--temperature guage (sea water);
--wide angle 35 mm cameras (for stereophotography);
--magnetometer;
--sub-bottom profiler (4 kHz);
--transponder interrogator (for navigation);
--emergency transponder;
--current meter;
--transponderrepeater(foroperating in very rugged terrain where shadowing from the transponder occurs);
--biological sampling net (multiple opening, used near-bottom;
--water sampling system;
--CTD system (Conductivity, Temperature, Depth measurements);
--slow-scan TV;
--sound velocimeter;
--side scan sonar.

Between 12 to 14 people standing round-the-clock watches are necessary to operate and maintain the system. The vehicle is handled over the side by a crane and has been operated in up to sea state 6. The fish dry weight is on the order of 2,000 lbs. The transponders used for navigation are normally suspended on a string about 300 m off the bottom. This altitude permits a reasonable range before near-bottom shadowing becomes a problem and the mooring string is short enough so that shifting of the transponder, owing to currents, is not a significant problem. Upward of 12 transponders can be deployed, depending on the size of the area being studied.

RUM. The system consists of a manned surface support buoy, umbilical cable, and a bottom-crawling vehicle. A constant-tension, cable-accumulator system in the barge (buoy) that maintains a constant lift force on the vehicle, which reduces its

10 ton in-water weight to about 2 tons and, thereby, reduces the possibility of its being buried in the sea floor.

Development of the RUM system began in 1958. The first generation system worked out from shore on the end of a reel of 30,000 ft of cable which it carried with it. TV pictures and 10 kw of power were transmitted over the cable. The shorter (10,000-ft.) cable was used in the second generation buoyed RUM. The track control system provided very good proportionate control and would permit us to station the manipulator, using the vehicle's track propulsion, within 1/4 in. of the object to be worked on.

The boom-mounted TV camera used was very successful, in that it allowed us to obtain different views of an object from various aspects of up to 2 m distance from RUM. Operations were conducted in sea states as high as 4 and 5.

Future Efforts

Our present concept envisions a combination of DEEP TOW and RUM capabilities into a vehicle that can be towed and lowered to the bottom to maneuver about and perform manipulative functions. It is also designed for sitting and observing on the bottom for up to 10 hours or longer. The vehicle will have caterpillar track-like propulsion and will weigh about 500 kg in water and about 200 kg in air. Its dimensions are about 2 x 2 1/2 m. There will be an onboard accumulator which accommodates ± 20 m of cable and maintains a constant tension of about 50 kg. The purpose of the accumulator is to keep the cable taut when the vehicle is on the bottom while decoupling the ship surge from cable forces from the vehicle. There will be two variable-pitch, counter-rotating thrusters at right angles to the cable mounted on a common turret atop the vehicle. Rotatable counterweights will permit adjusting for changes in the weight distribution on the vehicle and will also affect cable-induced overturning moments.

The work to be conducted by this new vehicle will more or less follow the work we have been doing with DEEP TOW but will allow more flexibility in our biological studies. In this latter work, we will look into planting respiration enclosures on the sea floor and subsequent recovery; observing benthic animal activity; and other tasks which are location intensive.

The control system will be bus-oriented with a master CPU and slave CPUs in the command and sensor areas to provide some processing and data reduction. Serial data links will be used to couple the concentrated computer inside the pressure cage to the exterior environment. The surface also will have a bus-oriented display and data recording system.

Two problems are salient concerning the ship's watch circle: 1) how to accommodate ship's heave (producing a longitudinal motion on the cable) and 2) to what extent we cab tolerate a horizontal vector on the cable. (Present assumptions are that the vehicle will be working with from 4 - 5 km of cable.) At five km, for example, a 50 kg force on the end of the cable will permit about a 300 m watch circle with the ship. At one km, the watch circle drops to 200 m (50 kg tension will be maintained on the accumulator). At 50 kg of force, we can tolerate 0.8 g cable acceleration before we arrive at a zero force situation.

Autonomous Vehicles in the Deep Ocean: Attributes of Different Vehicles

Table 1 presents the attributes of the various types of vehicles as they exist today. We can envision a number of very important and significant ways of employing autonomous vehicles in connection with other vehicles. In the cases of autonomous vehicles, where power is limited, and a tethered unmanned vehicle, there can be a mother/daughter relationship in which the autonomous vehicle would provide more than one observation point and could be recharged by the tethered vehicle if necessary.

Table 1
Vehicle Attributes

Manned Subs	Tethered, Unmanned	Autonomous
Communication via acoustic link: satisfactory	Coaxial cable or fiber optics: OK	Acoustic link: restrictive
Life support required Freedom of motion in hazard free water	No life support Entanglement potential	No life support Freedom of motion, no human safety hazard
Energy budget limit	Power budget limit	Energy budget limit
Limited mission time	Unlimited mission time	Limited mission time
Deep water ascent/ descent time--critical	Not critical	Critical
Buoyancy limited payload	Cable limited payload	Buoyancy limited payload
Diver required for dead stick recovery	Fail-safe dead stick recovery	Diver required for dead stick recovery
Reliable High degree of manipulation	Reliable High degree of manipulation	?? No manipulation

Where a manned and a submersible autonomous vehicle work in combination there is an interdependence in which mission time should be designed to be compatible with both vehicles. The types of work these combinations can conduct include the following:

Dump site observations (tethered and autonomous vehicle). In this mode, the autonomous vehicle would work from the tethered, bottomed vehicle and send its data back to it.

Selective placement of sensors, the autonomous vehicle could deploy an array of sensors.

Photography (the autonomous vehicle providing various supplemental lighting angles)

Antarctic Krill Studies (during ice-covered months)

Water Studies During Storms (physical oceanographic measurements/observations)

These are a few potential tasks where autonomous vehicles show significant potential. There are undoubtedly many other areas for application that will be revealed as this technology emerges in the future.

Summary of Technology Review (Navigation and Acoustic Communication)

Victor Anderson
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Scripps Institution of Oceanography
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Navigation

The following is a summary of the Short Baseline and Long Baseline acoustic transponder navigation systems in use in the oceans today.

Short Baseline (Range Bearing)	Long Baseline (Range/Range)
Number of Transponders Required	
single	three or more
BASE STATION	
Omni Transmit Directional Receiving Array Time Threshold Bearing Phase Measurements Single Frequency	Omni Transmit/Receiver Time Threshold Frequency Select
ERRORS (S/N Dependence)	
Cross Range $\sigma_{xR} \simeq \frac{\lambda R}{\sqrt{2}k(S/N)^{1/2}d}$ Down Range $\sigma_R \simeq \frac{C}{K(S/N)^{1/2}W}$	$\sigma = \frac{2}{K} \; \frac{C}{(S/N)^{1/2}W}$
Example $f = 7$ kHz; $R = 5$ kM; $W = 0.5$ kHz; $d = 2$ m	
$\sigma_{xR} \simeq 10$m $\sigma_R \simeq 0.1$m	$\sigma \simeq 0.2$m
AREA COVERAGE	
Circle, Radius = R_{max}	Circle, Radius = $\frac{R_{max}}{2}$ (3 transponder net)

OTHER ERRORS

Short Baseline	Long Baseline

BIOLOGICAL NOISE AND MIMICKING

Preventive steps against false travel times
----Range Gating and Tracking----

Arrival Angle tracking	

Accept center fractile of time delay distribution

MULTIPATH (DEEP WATER)

Arrival Angle identifies path	Evaluate alternate solutions with image transponders for surface path

MULTIPATH (SHALLOW WATER)

Arrivalangleidentification of path where time-separable. Ray trace interpretation of time delay *vs.* source position (short pulses best)	Tracking of arrivals to identify new order of thresholded multipath. Ray trace interpretation of time delays (will be different for different transponders; may require more transonders).

SOUND VELOCITY PROFILE

Cross range error from ray bending	

First order correction of time delays with average sound velocity

Higher order or ray trace correction might be required for near-surface refracted paths

SHADOWING BY STRUCTURES

Time jitter and masking aleviated with spatial diversity of receivers

CURRENTS

Motion of moored transponders - compute offset

Doppler time compression cancels to 1st order

Acoustic Communications

Deep Ocean Vertical Path

Using directional transducers, <45° from the vertical standard commercial modems and 11 kHz band center, 4 kHz band, 10 db S/N the following has been transmitted: 4800 bits per second from 15,000 feet with 1×10^{-5} bit error rate. Indications are that this can be pushed to 9,600 bits on the same bandwidth.

Horizontal Path

Short range; higher frequency permits using a broader band
Severe multipath can occur
Using m'ary FSK coding 40 bits/sec transmission were achieved in shallow water
Spatial selection of single path achieved 1800 bps using 45-50 kHz at 6.6 k ft range
Parametric sonar has been used for high directionality transmission to eliminate multipath (negligible side-lobes)

Summary of Technology Review (Artificial Intelligence)
Robert Corell
Marine Systems Engineering Laboratory
University of New Hamsphire

One of the more salient observations regarding artificial intelligence (AI), is that the major goal should be simply to use computers as intelligence amplifiers. Another way of conceptualizing it is: to provide intelligent assistance. Knowledge in the artificial intelligence community can be divided into two types: symbolic and signal. To the engineer this would be the difference between discrete and continuous systems, respectively. Carnegie-Mellon has developed the Harpy Speech Recognition System which is capable of: handling a 1,000-word vocabulary; recognizing the voices, inflections, etc., of 5 to 6 different individuals, and can take sentence structures and convert them back into words. While this has no immediate foreseeable application to autonomous vehicles, it does demonstrate some of the concepts that are being converted from theory in AI into practical operating systems that can solve artificial intelligence problems.

Five elements of knowledge have been conceptualized, at least in terms of approaching it from an AI point of view:

1) Identification: identify the class of thing one is working with to eliminate alternatives.

2) Acquire knowledge about the subject.

3) Mechanisms for representing knowledge (how does one describe it: gray scales, end-by-end pixels, or other methods?)

4) Mechanisms for utilizing knowledge.

5) Mechanisms for discarding alternatives (explanations).

Although the artificial intelligence community has had a difficult time in converting concepts into reality, there are a number of areas where real-world application has recently become increasingly apparent (e.g., vision, pattern recognition in photographs, speech recognition). These concepts and techniques will increasingly contribute to undersea activities.

Man-Machine Systems

One of the major questions in this area is: where does man fit into the robotic system?

Direct Manual Control: Commanding or Effecting--where man makes a conscious effort to make the system do something.

Information Feedback

Supervisory Control: In essence, man somehow "talks" to a computer system and the computer exercises control. Within this process there is a wide range of density of man's involvement in this process.

Teleproprioception: Where is my alter ego or where is my vehicle?

Levels of Automation: Where in the full spectrum, do we want our systems to operate? This should be a conscious decision rather than a decision that is a product of the fact that we have sophisticated microprocessors, sensors, and effectors that can perform various tasks. This decision can range from total automation to a fair degree of human involvement. Man's involvement or lack of involvement in the system should be decided in a careful, cautious, and deliberate way.

Psychophysiological Issues: One aspect of this involves task times invovling different types of manipulators and different display formats with manipulators.

Major Areas of Technology Requiring Research or Improvement: The following list identifies those areas of autonomous vehicle technology where additional research and development is indicated. Items that are underlined were felt, by conference participants, to be the most critical to future vehicle performance.

Vehicle dynamics
Vehicle control
Image processing
Artificial Intelligence
Navigation
Communications
Microprocessors
Mission analysis/work systems
Energy (vehicle power sources)
Guidance
Data sources/sinks
Support systems
Reliability (fault tolerance)
Materials
Cost/profitability/data

Research and Development Program, Conservation Division, U.S. Geological Survey

John B. Gregory
Conservation Division
U.S. Geological Survey
Reston, Virginia

The U.S. Geological Survey is the nation's earth sciences agency. It was established by an Act of Congress in 1879 and charged with the responsibility for classification of the public lands, and examination of the geological structure, mineral resources, and products of the national domain.

Since 1926, the Geological Survey has been responsible for the supervision of oil and gas and mining operations authorized under leases on Federal land. More recently, petroleum exploration on the Outer Contental Shelf (OCS) expanded the Survey's responsibilities. With the passage of the OCS Lands Act of 1953, the Survey was assigned the responsibility for assuring safe, pollution-free oil and gas operations on the OCS.

As a result of recommendations several years ago from the National Academy of Sciences, the University of Oklahoma, and the National Aeronautics and Space Administration (NASA), the Geological Survey has embarked upon a program of research and development to provide the technological insights needed for its regulatory operations offshore--operations that provide assurances to the public for safety and for the prevention of pollution in oil and gas drilling and production. These clear objectives are, therefore, those of the research program, not the economics of operations, which are of concern to industry.

The Program is a contract research program and is an integral part of the Conservation Division. It is a focal point for deriving possible solutions from the university community, private industry, and the Federal laboratory system for identified offshore operational problems. This vast interdisciplinary body of science and technology provides the kind of research needed by the Division in its Outer Continental Shelf (OCS) operations which involve such problematic areas as structural dynamics, fluid flow, and geotechnology.

For purposes of management, the Program is divided into three generic categories--structures and pipelines verification; well control, or the prevention of blowouts and consequent fires; and the effects on the environment from OCS operations.

With regard to offshore structures, in the fall of 1979 the Geological Survey established within the Conservation Division a Platform Verification Section whose task is to administer a program of offshore structures verification. This program was recommended by the Marine Board of the National Academy of Engineering in a 1977 report, "Verification of Fixed Offshore Oil and Gas Platforms." Since that time, the Survey, with the Board's guidance, has been devising requirements for the design and initial inspection of new fixed and bottom-founded platforms. These structures consist of all the new OCS platforms to be erected outside the Gulf of Mexico (including gravel and ice islands), new structures within the Gulf to be located in water depths greater than 400 feet, structures whose natural fundamental periods exceeds 3 seconds, those to be located on an unstable bottom, or those of unique design. The Survey's requirements are detailed in the publication, "Requirements for

Verifying the Structural Integrity of OCS Platforms," October, 1979.

Though initial inspections are required after platform installations are completed, at present no decisions have been made by the government on requirements for subsequent periodic inspections. North Sea experience, however, indicates that for some of the above-mentioned situations, mandatory underwater inspections of some type will be quite likely. Even if not required, the Survey needs an understanding of the latest technologies for such factors as design, inspection, remote monitoring, and the determination of failure probabilities.

With regard to pipelines, the Geological Survey is basically responsible for assuring the integrity of about 25 percent of the lines (mostly gathering lines) on the OCS. The remainder are under the jurisdiction of the Department of Transportation. Although the Federal Government does not require underwater inspection, it must keep abreast of new technologies for detecting leakage and other pipeline irregularities; the regulatory agencies need to be informed and to maintain a certain level of proficiency.

Several basic technologies, involving various combinations of instruments, submersibles, technicians, and divers, are presently used by industry to verify the integrity of offshore platforms and pipelines. When viewing advancements in technology over recent years in this field, as well as for other ocean engineering applications, no single inspection procedure has sufficed. Instead, the basic methods now in use probably will be improved and will be used for years to come. As evidenced by

NASA's space ventures, both manned and unmanned systems have their places because of the complementary advantages they provide.

From accumulated experiences, however, the use of divers in relatively deep, harsh environments such as the North Sea is not only very expensive, but also quite dangerous. These factors suggest a thorough search for alternative means of inspection. Several years ago, the results of such a search might not have been encouraging, but from time to time key breakthroughs occur to cause technological advances that dramatically change the ways people do things; the jet engine and transistor are examples. At the heart of the very latest advance is the microprocessor. When combined with several other relatively new developments, such as large-scale integrated circuits, high energy-density batteries, and optical fiber signal transmission, it allows technologists to seriously explore the field of robotics. To replace man underwater by a supervised robot or an almost autonomous vehicle that could navigate, inspect, perform useful services, and communicate would be quite innovative. This technology is under development by the Research Program in a project called EAVE, Experimental Autonomous Vehicles.

EAVE makes use of testbed vehicles fabricated by the University of New Hampshire (EAVE East) and the Naval Ocean Systems Center (EAVE West). The project is a collaborative effort between these organizations. At the Naval Ocean Systems Center an open-frame torpedo-like submersible, has been constructed as a testbed to study magnetic navigation and optical fiber communications. This vehicle is powered by lead-acid batteries which, together with electronics, are located in the four canisters within the vertical frame. Twin propellers located aft, and a vertical propeller amid-ships, between syntactic foam buoyancy blocks, provide propulsion for the vehicle. A second testbed, this one roundish and able to propel itself in any direction, is being developed by the University of New Hampshire where work is being conducted on acoustics for both navigation and communications. This testbed has twin electrical thrusters on three orthogonal axes and is controlled by electronic equipment located in pressure cases mounted on the frame. Just below that frame is a ring upon which, for purposes of navigation, 12 equally spaced acoustic sensors are mounted. At the very top are two buoyancy cylinders.

For more information on the EAVE project or on the projects of the Research and Development Program, write to the U.S. Geological Survey, 620 National Center, Reston, VA 22092 for Technical Report 1981, Open File Report 81-704.

OTHER SPEAKERS

The participants listed below spoke on the topics which appear under their name. Unfortunately, no record or text was available for publication.

Raj Reddy, Carnegie-Mellon University
Artificial Intelligence

Dale Chayes, Lamont Doherty Geological Observatory of Columbia
Deep Water Search for the Titanic - Limitations of Tethered Vehicles, Advantages of Autonomous Systems

Commander Van Neild, Defense Mapping Agency
Under Ice Hydrography

Ian Morris, University of Maryland
Ocean Science

APPENDICES

BENTHIC 4800 BITS/S ACOUSTIC TELEMETRY

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In June, 1981, continuous 4800 bits/s digital data was acoustically telemetered in 15,000-foot deep water from a near-bottom instrumentation package to a surface platform. As the platform drifted from overhead to an offset angle greater than 45° from the vertical, over 1.0×10^7 bits of pseudo-random digital data were transmitted with a total of 10 received errors, yielding an average bit error rate of 1×10^{-6}. For the same experimental conditions 2.6×10^6 bits of 1200 bits/s data were transmitted downward without making a single error.

In addition to the digital data, voice, pings, tones and slow-scan television were transmitted. All transmissions were at a transducer input power level of 33 Watts and were between 8 and 14 kilohertz. The modulation technique used was dual independent sideband with an injected pilot tone to provide for doppler correction. Within each independent sideband, the pseudo-random digital data was transmitted using quad differential phase shift keying and slow-scan television data was transmitted using non-orthogonal frequency shift keying.

These results are the culmination of a 5-year effort to determine the limitations on high data rate telemetry imposed by the near vertical ($\sim 0^0$-45°) acoustic channel. The pop-up instrumentation package BUMP (Benthic Untethered Multipurpose Platform) was used throughout these tests as an acoustic source and receiver. The main features of this package and accomplishments of earlier tests will be discussed along with the aforementioned results.

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COMPUTER SYSTEMS FOR AUTONOMOUS VEHICLES

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ABSTRACT

The advent of the microprocessor has permitted a substantial amount of computing power to be placed in underwater automata for inspections, work, and other tasks under conditions where tethers are not desirable. Hardware costs are low and power consumption minimal.

This paper examines the impact of the microprocessor computer on the autonomous vehicle. The trend toward distributed processing, and the increasing memory size, and the consequent impact on mission capabilities, communication, navigation and control are reviewed.

Software design guides the reliability and effectiveness of the hardware, and demands a major portion of development effort. Progress in user oriented languages, software system design, and in flexibility between system elements is described.

Ocean technology is going through a revolution with the advent of the microcomputer. The ability to apply powerful computers and their processing capabilities at minimal cost presents an opportunity to address far more complicated problems than ever could be attempted before. The problems of ocean science and engineering are no exception.

Evolution of man in the sea has resulted in a new class of complicated problems which truly challenge our abilities to deliver. As oil exploration concerns itself with deeper water and the ocean scientist with developing a more complete understanding of deep ocean processes, the need arises to place a new class of automata in the ocean to do man's work.

Underwater work systems using divers and/or one-atmosphere manned submersibles have been, and continue to be, indispensable in performing missions with requirements dictating their use. These systems, however, carry the burden of high capital and operating costs, low payloads, and the necessity of maintaining and protecting human life.

Unmanned, tethered submersibles have accumulated an impressive record in performing numerous underwater missions. Their drawback is the tether cable which causes cable drag, depth limitations, restricted maneuverability, danger of entanglement and significant cable-handling complexities which increase both capital and operating costs.

For more than a decade the unmanned untethered submersible has been used as a tool for underwater work. Increasingly this work has taken advantage of the developments in microcomputer technology to help solve the problems of eliminating or at least minimizing man from the vehicle system.

The EAVE-East program at the Marine Systems Engineering Laboratory (MSEL) has been tasked to address the needs of underwater inspection. The evolution of the system and its ability to address more complex tasks has been tied directly to its on-board microcomputer system and the computational capabilities which result. A brief summary of this evolution at MSEL typifies the microcomputer impact on the development of an unmanned untethered vehicle system. EAVE-East's original mission, that of following an exposed underwater pipeline, was addressed with a single IM-6100 microcomputer system. The addition of a Motorola 68000 microprocessor controlling three 6100 based microcomputers allowed the vehicle to address the much more complicated mission of navigating itself through an undersea structure in order to perform inspection tasks. Current development efforts to incorporate high level languages (Pascal, "C") within the computer system will allow the application of very complex algorithms and increase the on-board intelligence. Each increase in the machine intelligence lessens the necessary operator involvement and permits more closely the attainment of a truly autonomous submersible vehicle.

It is important to recognize the difference between intelligent systems and controlled systems. Many applications of microcomputers to ocean systems may be classified as controllers, i.e., systems which step through a logical sequence of defined steps to perform a function. The

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sequence of events may be modified by sensor inputs but these inputs are deterministic in nature and the system response to these inputs has been previously defined. A truly autonomous system, on the other hand, is defined as a system capable of sensing, thinking, and acting. It can sense external or internal phenomina, make decisions which are based on this information and execute the appropriate action based on those decisions.

Although the final goal is to develop an unmanned untethered vehicle system which is truly autonomous and does not require any human interaction, it is much more reasonable, for the near future, to understand the impact of microcomputers on the technologies required for a semi-autonomous system.

A Symposium on Unmanned, Untethered Submersible Technology held at the University of New Hampshire in 1980 considered several technology areas which impacted greatly on the development of unmanned untethered vehicles. Their discussion isolated the 10 technologies listed in Table 2. Of these, six rely heavily on the computational power which is part of the vehicle system. The following paragraphs summarize the impact of the microprocessor on those six areas.

<u>Control/Vehicle Dynamics</u>

One of the basic needs of current autonomous vehicle systems is the need for a well defined control strategy and the required computational capability, on-board, to impliment the necessary control equations. The control technology is available and can be applied to the vehicle problem, however, the resulting algorithms place such high demands on the on-board processor that a simplified solution has usually been implimented.

The vehicle must respond to sensor inputs possessing random components that affects precision, as well as average level changes that affect accuracy. The computer must then apply advanced filtering techniques to generate a fully valid set of input commands from what is essentially its noisy universe. The control system must then respond to the commands with a full understanding of the constraints of the vehicle itself.

Initial EAVE-East vehicle control, due to limitation on the computational capabilities, used a simple single dimension open loop control algorithm. With the addition of the 68000 microcomputer, a two-dimensional control system addressed the problem of traversing a simple undersea structure. Current work is taking advantage of the on-board computational power to impliment a control strategy which accounts for non-linear control and real vehicle dynamics to allow the vehicle to respond in up to five degrees of freedom, each of which may be cross-coupled. The control problem is a tractable one with a competent computer, and is one that may not be ignored if efficient operation in critical environments is to be attempted.

<u>Communication</u>

Communication with an unmanned, untethered submersible is most realistically addressed through the use of acoustic telemetry. The channel involved is notoriously bad.

Initial designs used microcomputers to control the transmitter and receiver hardware, i.e.; start the transmit sequence; adjust receiver gain; store results. Further efforts led to highly controlled acoustic hardware which was adaptive to channel characteristics and the inclusion of error detecting and correcting to improve data reliability, however, the effective data bandwidth still remains small. Current efforts are now taking advantage of large fast memories and more complex algorithms to extract information from the acquired data and transmit only the information implicit in the data, thereby decreasing the bandwidth requirements. An example of the difficulties may be seen if it is required to present video data of minimal resolution (256 x 256) to a remote operator while using an acoustic link. A quantity of over 4 million bits of data would have to be compressed more than three orders of magnitude to pass through the channel. The solution of such problems, however, can now be considered if the designer can understand and effectively use available microcomputer processing capability, to extract the essential information from the data stream.

<u>Navigation</u>

Navigation is one of the most important functions of an autonomous system. It is also unique in that it must usually acquire data from multiple sources to form a reliable coordinate estimate. Once acquired, the data must be filtered, judged for accuracy, and combined with the navigation algorithms to develop a position fix. This process, though relatively well defined, becomes very complex when the means for periodic intelligent control are not readily available from an operator.

Microcomputer-based systems are well configured for systems which require periodic access to sensor data. Advantages result when the on-board memory is used to develop history or probalistic understanding of the incoming data. Further benefits result when the on-board memory is used to store a mapping of the area, or volume, of interest which can be referenced at mission time. Future efforts may well take advantage of video or acoustic images and process the data in those images to obtain necessary three dimensional navigation data.

Artificial/Machine Intelligence

The decision making process requires that the machine decide from available information what action it must take to accomplish its task. That information is either preprogrammed in an on-board database or acquired from on-board sensors or, more properly, both. This process requires application of the techniques being addressed in the area of artificial intelligence and consumes prodigious amounts of memory and computational power. With the advances in memory speed and computational capabilities it is now possible to apply some of this work to autonomous vehicle development efforts.

Manipulations/Work Systems

The application of manipulators or work systems to unmanned untethered vehicle systems place large demands on not only the computational power, but also the memory size and software system flexibility. The added control problem impacts greatly on the original control strategy of the platform and complicates an already complex control algorithm.

Although initial missions involve only passive inspection missions, currently work is underway to examine simple active work tasks leading to supervisory control of on-board manipulators. As microprocessor speed and power increases, and size and power constraints shrink, it will be possible to consider the application of the work which has been done with terrestial robots to underwater automatons.

Sensors

Currently unmanned untethered submersibles are uniquely suited to inspection tasks where they can act as a platform for various inspection sensors. Capable sensors which will gather data to accomplish specific tasks require a high level of control when they are used without the supervision of trained operators. This control must be provided by the vehicle system. A broad range of sensors will require varying degrees of computational capability from a temperature measurement to a CCD camera which can make video data available to the processing capabilities of the vehicle system and the results used as input for future decision making algorithms. It is clear, however, that inspection needs become greater and sensors more complex, a large burden is placed on the vehicle system to provide more and more intelligent control of the required sensor.

Microcomputer System Capabilities

To further understand the impact of microcomputers to the above technology areas, it is necessary to look at the advances which have been made in integrated circuit technology. The advances can be grouped into three areas each of which allow solutions to be developed which could not have been considered in the past: 1) Microprocessors 2) Memory Systems 3) Software Systems.

• The wide range of microprocessors available at low cost offer great flexibility in design of ocean systems. They range from 1 bit controllers to the newer 16 bit devices which rival some of the currently used mainframe computer systems. The speed and power of their instruction sets allow the solution of complex equations which are required for system control strategies and demanding sensor processing or calibration tasks. As an example the Motorola 68000 microporcessor may be compared favorably with Digital Equipment's DEC PDP 11/40 (Table I) which is currently used for many of these computational tasks. This capability opens the door to the possibilities for addressing the more involved problems associated with unmanned untethered vehicle systems. Even more power is available through the use of a distributed processing architecture that uses many processors in a single vehicle computer system. This architecture allows modular development where each module performs a single function within the system. An example might be a separate navigation microcomputer system, which handles all of the data acquisition tasks and processing required to generate an accurate position. This position is then available for the vehicle system components. Distributed processing is a well recognized architecture, however, it has a unique advantage for an underwater system since it allows a self-contained system (pressure case) to be connected to other system components through a simple 3 wire physical connection.

It would be shortsighted to believe that computational power alone is sufficient. The memory system has great demands placed on it. The memory system required for an unmanned untethered vehicle system may be divided into three classes 1) main memory to contain program instuctions 2) fast auxiliary memory for intermediate access by the microprocessor for various tasks 3) fixed-media mass storage for longer term non-volatile storage. With the inevitable use of high level languages the memory system must be large. The advances in memory technology, however, have lowered the price, size, and power to a point where very large main memories and fast read-write memories are quite practical. The cost of storing one bit of information has been reduced by 98% in 10 years to less than .03 cents. These developments have also provided solutions to reliable, low power, fast access storage through the use of magnetic bubble technology. The availability of large memories now allow the implementation of large, memory intensive programs such as those developed by researchers in artificial intelligence. Their algorithms demand great quantities of available memory which can be accessed rapidly. These same large memories allow for the storing of necessary information to make an autonomous vehicle adaptive to new or modified mission tasks.

The software system development may indeed be the newest challenge to the ocean engineer. Many of the more demanding problems which arise during system development, surface within the software system. The cost of software development is great, however, much effort is being addressed to increase the productivity of the programmer. The use of high level language and modular programming techniques can do a great deal to minimize the software burden. The ability to impliment these high level languages within the on-board computer system offers a high powered tool for the solution of complex problems. It is now possible to use a language which is designed to meet a specific need. Pascal may indeed be best for one mission, but LISP may best be used when dealing with others. This flexibility offers great advantage to the development efforts of autonomous vehicle systems.

Along with the availability of high level languages are the advances in the development of hardware aids which support software development. This equipment facilitates the development and debugging of software as well as the debugging of hardware through in circuit emulation. The availability of multiuser develoment systems to perform these functions aids the design process greatly.

Increased Performance

The advances in microcomputer technology which now offer such flexibility and opportunity in the solution of the many problems to be addressed in the development of autonomous vehicle systems are continuing. Many new ideas are leading to even more exciting tools which will be available to the ocean engineer.

The demands for increased performance in many application areas is forcing the development of computers which will not be limited to the sequential operation of the von Neumann architecture. Computers with unconventional architectures - parallel processing, pipelining, relational data base management and multilevel redundancy - are being developed. With the availability of this computational power, it is possible to consider sensors which require real-time image processing, complex signal processing, and extended missions with goal oriented tasks. One of the most prominent examples of architectural evolution in microcomputers is the Intel IAPX432. The hardware and the operating system are designed to mesh with a high level application language (ADA). The architecture is object-oriented and the 16 million memory blocks provide ample space for the objects. The 432 architecture is designed such that multiple processors can be added or eliminated without software modification as system needs expand or contract. This architecture combines the hardware, its operating system, and the high level language it supports as an architectural unit thereby helping to eliminate many of the tedious design chores which must now be faced during system design.

These advances offer the tools which can be applied to the development of a truly autonomous undersea robot. Autonomous vehicle systems must draw heavily on this work as missions grow more complex and operator interaction further eliminated.

In summary, it must be stated that boundaries do exist which restrict the use of microcomputer based systems. The learning process which results from a good understanding of any specific microprocessor and its support chips is a long and costly one. With this understanding, it is obviously wrong to use a new and different microprocessor with each new application. Similarly software capability results only when programmers are at a point quite high on the learning curve with a specific language. It is beneficial to commit design groups to specific hardware and software and develop universal pieces which have been well documented and debugged. This allows the develoment of libraries of software subroutines and hardware components which can be configured to solve specific design problems.

Even with these restrictions the microcomputer is now, and will continue to be, the most exciting and powerful design tool available for the solution of problems to be addressed in the development of autonomous free-swimming submersibles.

TABLE 1

COMPARISON OF 68000 TO SOME OTHER PROCESSORS

	68000	PDP 11/40	LSI-11	8086	6100(PDP-8)
Direct Memory Space	16 MByte	65KByte	65Kbyte	1 MByte	4K x 12
CPU Registers	17 - 32 bit	7 - 16 bit	7 - 16 bit	17 - 16 bit	2 - 12 bit
Hardware MPY/Divide	signed/ unsigned	signed	signed	signed/ unsighed	no
32 Bit Arithmetic	yes	no	no	no	no
Addressing Modes	12	12	12	8	3
Stack Oriented	yes	yes	yes	yes	no
Execution Time	@ 8MHz				
R to R move	0.5μs	0.9μs	3.5μs	0.4μs	2.5μs
Memory to R	1.5μs	2.25μs	7.0μs	2.8μs	2.5μs
Indirect	1.0μs	1.88μs	4.9μs	2.6μs	3.75μs
Indexed	1.5μs	2.50μs	4.9μs	4.0μs	
CPU Power :	1.2W		19W	1.2W	.02W

TABLE 2

UNMANNED UNTETHERED TECHNOLOGY DEVELOPMENT AREAS

- Control/Vehicle dynamics
- Communication
- Navigation
- Artificial/Machine Intelligence
- Sensors Control and Data Acquisition
- Manipulators/Work Systems
- Energy Storage

ASSOCIATED MICROELECTRONIC DEVELOPMENT AREAS

- Microcomputer Systems
- Digital Signal Processing
- Data Base Management

GENERAL PURPOSE DIGITAL SIMULATION OF UNDERWATER VEHICLES

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ABSTRACT

This paper is a summary of a real time simulation of a remotely-manned underwater vehicle control system in the Man-Machine System Laboratory at MIT. A non-linear model which is able to simulate the tight maneuvering of the vehicle is presented. This paper also categorizes various automatic control tasks of the vehicle .

INTRODUCTION

Because of the ocean's natural resources, recently much engineering attention has been focused on underwater technology. This has included the design and development of a series of remotely-manned underwater vehicles for depths too deep for human divers. These vehicles have been used for the inspection and repair of underwater structures and the exploration of the ocean environment.

This report emphasizes :
1) Dynamic behavior of underwater vehicles.
2) Analysis and design of some basic servo controllers for underwater vehicles.
3) Use of servo controllers in some complicated tasks like following the cotour of the ocean bottom.

MODELLING

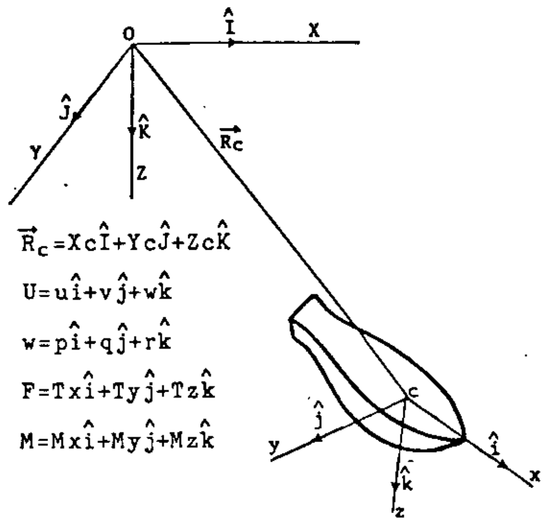
Our model uses two orthogonal coordinate systems. One remaines fixed at the water surface while the other travels with the submarine to act as a local reference system.

The position of the vehicle can be specified by reference to the axis OXYZ (on the surface of the water), and to use the rectangular coordinates Xc,Yc,Zc. the usual approach for orientation of the vehicle is to start with cxyz parallel to OXYZ and bring the vehicle from this reference orientation to its actual one by:
1) a " swing " around z axis, ψ ,
2) a " tilt " around yaxis, θ ,
3) a " heel " around x axis, ϕ .
Therefore, the vehicle may be located in space by:
A) Three position coordinates Xc,Yc,Zc.
B) Three angular coordinates ϕ , θ and ψ.

From Newton's law,

```
Tx-DRx-B*SIN(θ)         =M*[u+q*w-r*v-
Xg*(q**2+r**2)+Yg*(p*q-r)+Zg*(p*r+q)]

Ty-DRy-B*COS(θ)*SIN(φ)=M*[v+r*u-p*w-
Yg*(r**2+p**2)+Zg*(q*r-p)+Xg*(p*q+r)]

Tz-DRz-B*COS(θ)*COS(φ)=M*[w+p*v-u*q-
Zg*(p**2+q**2)+Xg*(r*p-q)+Yg*(q*r+p)]
-----------------------------------------

Mx-DRxx=Ix*p+(Iz-Iy)*q*r+M*[Yg*(w+p*v-u*q)
-Zg*(u+u*r-w*p)]

My-DRyy=Iy*q+(Ix-Iz)*r*p+M*[Zg*(u+q*w-r*v)
-Xg*(w+p*v-u*q)]

Mz-DRzz=Iz*r+(Iy-Ix)*p*q+M*[Xg*(v+r*u-p*w)
-Yg*(u+q*w-r*v)]
```

where
$u\hat{i}+v\hat{j}+w\hat{k}$ = velocity of the vehicle with respect to the attached frame.
$p\hat{i}+q\hat{j}+r\hat{k}$ = angular velocity of the vehicle with respect to the attached frame.
$DRx\,\hat{i}+DRy\,\hat{j}+DRz\,\hat{k}$ = drag force acting on



$$\vec{R}_c = Xc\hat{I}+Yc\hat{J}+Zc\hat{K}$$

$$U = u\hat{i}+v\hat{j}+w\hat{k}$$

$$w = p\hat{i}+q\hat{j}+r\hat{k}$$

$$F = Tx\hat{i}+Ty\hat{j}+Tz\hat{k}$$

$$M = Mx\hat{i}+My\hat{j}+Mz\hat{k}$$

Fig.1 Coordinate systems

the body.
$DRx x\hat{i}+DRy y\hat{j}+DRz z\hat{k}$= drag moment acting around the body.
M, Ix, Iy, Iz = mass and principal moment of inertia around C.
B= bouyancy force.
$Tx\hat{i}+Ty\hat{j}+Tz\hat{k}$= thrust force acting on the body of the vehicle.
$Mx\hat{i}+My\hat{j}+Mz\hat{k}$= thrust moment produced by the thrusters.
$Xg\hat{i}+Yg\hat{j}+Zg\hat{k}$= vector distance of the center of the gravity from c.

The state variables of the model can be calculated with respect to the inertia frame by the matrix transformations:

$$\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix} = \begin{bmatrix}1 & \text{SIN}(\phi)*\text{TAN}(\theta) & \text{COS}(\phi)*\text{TAN}(\theta)\\ 0 & \text{COS}(\phi) & -\text{SIN}(\phi)\\ 0 & \text{SIN}(\phi)*\text{SEC}(\theta) & \text{COS}(\phi)*\text{SEC}(\theta)\end{bmatrix}\begin{bmatrix}p\\ q\\ r\end{bmatrix}$$

$$\begin{bmatrix}\dot{X}c\\ \dot{Y}c\\ \dot{Z}c\end{bmatrix} = A\begin{bmatrix}u\\ v\\ w\end{bmatrix}$$

where A is

$$\begin{bmatrix}\text{COS}(\psi)*\text{COS}(\theta) & \text{COS}(\psi)*\text{SIN}(\theta)*\text{SIN}(\phi) - \text{SIN}(\psi)*\text{COS}(\phi) & \text{COS}(\psi)*\text{SIN}(\theta)*\text{COS}(\phi) + \text{SIN}(\psi)*\text{SIN}(\phi)\\ \text{SIN}(\psi)*\text{COS}(\theta) & \text{SIN}(\psi)*\text{SIN}(\theta)*\text{SIN}(\phi) + \text{COS}(\psi)*\text{COS}(\phi) & \text{SIN}(\psi)*\text{SIN}(\theta)*\text{COS}(\phi) - \text{COS}(\psi)*\text{SIN}(\phi)\\ -\text{SIN}(\theta) & \text{COS}(\theta)*\text{SIN}(\phi) & \text{COS}(\theta)*\text{COS}(\phi)\end{bmatrix}$$

$\dot{X}c\hat{I}+\dot{Y}c\hat{J}+\dot{Z}c\hat{K}$ = velocity of the vehicle with respect to the inertia frame.

SERVO CONTROLLERS

We wish to design three basic servo controllers for the vehicle: 1) an orientation controller, 2) a position controller, and 3) a speed controller. With the help of the above controllers the operator can reposition the vehicle to some arbitrary point in 3-dimensional space with any orientation or follow a trajectory.

The functions of the orientation controller are:
1) To overcome the rotational disturbances imposed on the body of the vehicle.
2) To bring the vehicle to the desired orientation as fast as possible. (The power of the thrusters and their time constants pose some limitation on this).

The "Estimator and Control Law" method was used to design the orientation controller. The estimator receives three different angles from three different inclinometers and produces all states of the model such as angular velocities. The estimator is corrected every sampling time by comparing its output with the actual measured angles.

With the help of the "Control law" method, which uses the state variables generated by the estimator, the orientation controller loop can be closed.

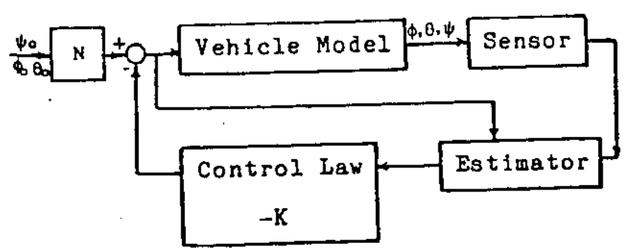


Fig.2 Estimator mechanization

The same idea is used for the velocity controller and the position controller. The velocity estimator receives three different translational velocities, and produces all the variables needed for the feedback loop. The inputs to the position estimator are collected from several sonar systems on board and on the vehicle. The position controller observer also produces all state variables needed for the feedback loop.

BOTTOM FOLLOWING

Path following is an algorithm that enables the vehicle to follow a path under the water at small and constant distance from the ocean bottom contour. The operator takes the vehicle to a certain depth, then turns the vehicle in the horizontal surface to a desired orientation. (In other words, the operator assigns some yaw angle to the vehicle). After the operator starts the path following program, the vehicle is able to follow the contour of the bottom at the assigned distance, at the specified yaw angle.

This algorithm enables the vehicle to follow any path without colliding with the ocean floor and maintain constant orientation. The algorithm uses the position controller to keep the distance between the vehicle and the bottom in the assigned distance; it also uses the velocity controller to achieve the desired speed along the path.

The vehicle is equipped with four sonar sensors, A, B, C and D in figure 3.

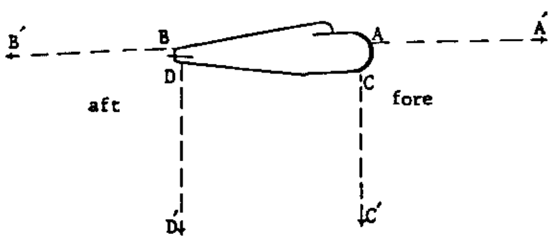


Fig. 3

A and B measure the forward and rearward distances, while C and D measure the distances between the vehicle and the ocean bottom.

The more knowledge about the environment is collected for the algorithm, the better the vehicle can follow the path. To insure that the vehicle recognizes the environment all paths can be divided to three categories:

1) Paths with slopes between 45° and 90°
2) Paths with slopes between -45° and 45°

3) paths with slopes between -90° and -45°

Dividing the bottom contour into three categories is essential for the vehicle to make automatic control decisions. If the measured distance from sonar A is smaller than the other sonars, then the vehicle is in an environment of type 1 and the closest part of the vehicle to its environment is point A.

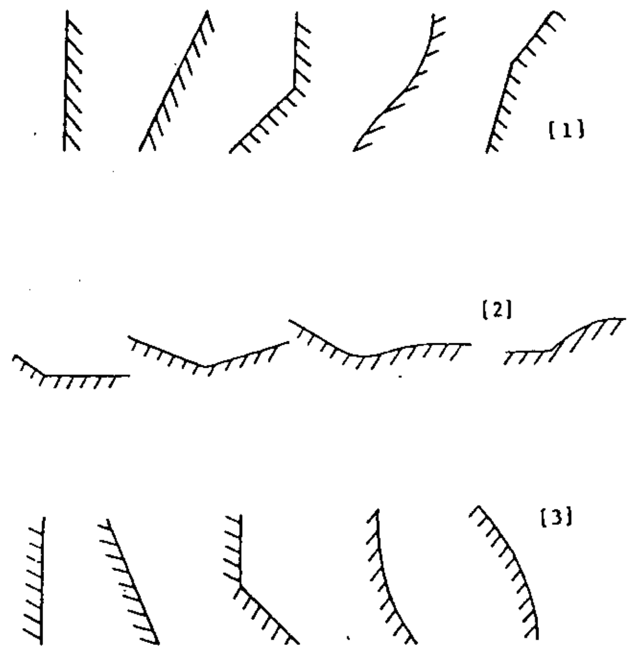


Fig.4 Three categories of environment contours.

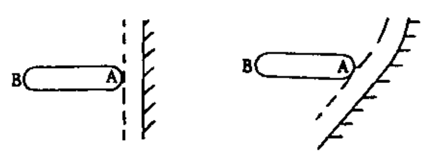


Fig.5 Vehicle moving in environment of type 1 .

In any path of type 1 there is always some danger that the vehicle will collide at its bow. If the measured distance from sonar B is smaller than that of the other sonar sensors, then the vehicle is in an environment of type 3 and point B is the closest part of the vehicle to its environment.

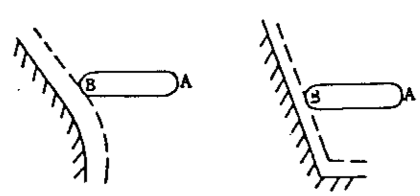


Fig.6 vehicle moving in environment of type 3 .

The following shows the logic to realize the environment.

$$\text{If} \begin{cases} AA' < BB' \\ AA' < CC' \\ AA' < DD' \end{cases} \longrightarrow \text{type 1}$$

$$\text{If} \begin{cases} CC' < AA' \\ CC' < BB' \\ \text{or} \\ CC' < AA' \\ CC' < BB' \end{cases} \longrightarrow \text{type 2}$$

$$\text{I} \begin{cases} BB' < AA' \\ BB' < CC' \\ BB' < DD' \end{cases} \longrightarrow \text{type 3}$$

If the vehicle is in an environment of type 1, the algorithm realizes that the measured distance from sonar A is the smallest measurement. Then the vehicle uses its horizontal thrusters to keep AA' in the assigned distance. The horizontal thrusters are run by the position controller.

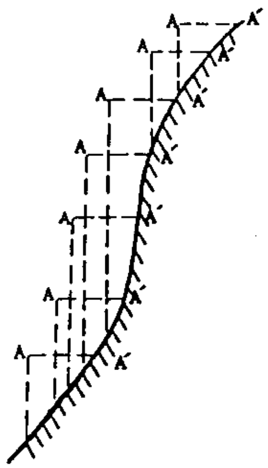


Fig. 7 In path of type 1 , AA' is kept in the assigned distance.

If the vehicle gets closer or farther from the bottom because of any disturbance (for example ocean currents), then the position controller will overcome the disturbance and will bring the vehicle to the desired distance.

One must use the vertical thrusts to vary the speed along a type 1 path such as that shown in figure 7 . The control algorithm uses the speed controller to run the vertical thrusters. Vertical movement of the vehicle by means of the vertical thrusters and speed controller causes the forward distance to change, which in turn can act like a disturbance for the position controller. This disturbance must be overcome by position controller.

In other words, there can be some mutual forcing or cross-coupling by the control systems.

If the vehicle is in an environment of type 2 , the vertical thrusters are run by position controllers to keep CC' or DD' in the desired range. The horizontal thrusters are run by speed controller . Any horizontal movement causes some change in the vertical distance CC' or DD' , which can be overcome by the position controller. In an environment of type3 , the algorithm works the same as it does in type 1.

The entire underwater vehicle control system is being modelled in the Man-Machine System Laboratory at MIT on an 11/34 computer. Figure 8 shows this simulation configuration . An electric wheeled vehicle equipped with a camera is able to simulate the motion of the underwater vehicle in the laboratory. Alternatively, a Megatek stroke writing display can be used to show a continuously moving three-dimensional graphical simulation of the underwater vehicle.

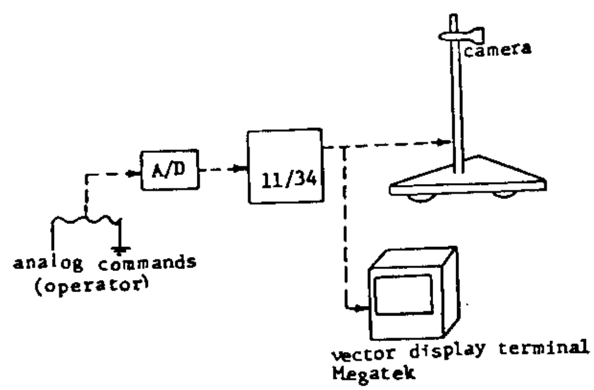


Fig. 8 Underwater simulation in the laboratory.

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SECOND INTERNATIONAL SYMPOSIUM ON

UNMANNED, UNTETHERED SUBMERSIBLE TECHNOLOGY

New England Center for Continuing Education
Durham, New Hampshire

Monday, September 21, 1981 - Kearsarge Room

7:30 a.m. - 8:30 a.m.	Registration - Coffee & Danish
8:30 a.m. - 9:00 a.m.	Introduction: Gene Allmendinger; Conference Chairman Eveleyn Handler; President, University of New Hampshire

NEW PROGRAM DEVELOPMENTS
UPDATE ON CURRENT PROGRAMS

9:00 a.m. - 10:30 a.m.

EAVE-WEST	Paul Heckman Naval Ocean Systems Center San Diego, California
ROBOT	Tom Sheriden Massachusetts Institute of Technology
AUSS	Jerry Mackleburg Naval Ocean Systems Center San Diego, California

10:30 a.m. - 11:00 a.m.	Coffee Break
11:00 a.m. - 11:45 p.m.	Resource Speaker:
Remotely Controlled Vehicles: What Are Their Limits?	Drew Michel Taylor Diving Inc.
11:45 p.m. - 1:30 p.m.	Lunch: Mystic Room New England Center

1:30 p.m. - 3:00 p.m.

NRL	Earl Carey Naval Research Laboratory
ASCOP	.... Naval Coastal Systems Center
EAVE EAST	Dick Blidberg Marine Systems Engineering Lab University of New Hampshire

3:00 p.m. - 3:30 p.m.	Break

3:30 p.m. - 5:00 p.m.	Symposium Speaker:
Microcomputer Development Trends With a Look Towards the Future	Jeff Hawkins Intel Corporation
5:30 p.m. - 7:00 p.m.	
Informal Discussions	Elliot Alumni Center (refreshments courtesy of Datasonics, Inc.)
Dinner	Personal arrangements

Tuesday, September 22, 1981 - Kearsarge Room and Narraganset Room

9:00 a.m. - 11:00 a.m.

ARCS	John Brook Bedford Institute of Oceanography
EPAULARD	Jean-Louis Michel Cnexo
ROVER	Heriot-Watt (video tape)
SPURV	Applied Physics Lab (unable to attend) University of Washington
9:30 a.m.	Coffee
11:00 a.m. - 12:00	
Sonar Image Processing for Underwater Robots	Raj Reddy, Chuck Thorpe Carnegie Mellon University
Underwater Cameras Today	Steve Eppig Hydro Products
12:00 - 1:30 p.m.	Lunch - personal arrangements

TECHNOLOGY REVIEW SESSIONS

Vic Anderson Marine Physics Lab Scripps Inst. of Oceanography	Bob Corell Marine Systems Engineering Lab University of New Hampshire

1:30 p.m. - 3:00 p.m.	**TECHNOLOGY REVIEW #1** - Bob Corell Kearsarge Room
Artificial Intelligence	Raj Reddy Carnegie Mellon University
	TECHNOLOGY REVIEW #2 - Vic Anderson Narraganset Room
Navigation	John Loud, Woods Hole Oceanographic Institute
3:00 p.m. - 3:30 p.m.	Break

3:30 p.m. - 5:00 p.m.	**TECHNOLOGY REVIEW #3** - Bob Corell Kearsarge Room
Man Machine Systems	Tom Sheriden, Massachusetts Institute of Technology
	TECHNOLOGY REVIEW #4 - Vic Anderson Narraganset Room
Acoustic Communication	Jerry Mackelburg, Stan Watson Naval Ocean Systems Center
Dinner	Personal arrangements

Wednesday, September 23, 1981 - Kearsarge Room and Narraganset Room

9:00 a.m. - 11:00 a.m.	**TECHNOLOGY REVIEW #5** - Bob Corell Kearsarge Room
Microcomputers	Dick Bildberg, Dick Lord Marine Systems Engineering Laboratory
	TECHNOLOGY REVIEW #6 - Vic Anderson Narraganset Room
Control System	Damon Cummings Draper Laboratories
9:30 a.m.	Coffee
11:00 a.m. - 12:00	**Resource Speaker:**
Deep Ocean Applications: (Poly metallic sulfides/ nuclear waste)	David Duane NOAA/Sea Grant
12:00 - 1:30 p.m.	Lunch - personal arrangements
1:30 p.m. - 3:00 p.m.	**TECHNOLOGY REVIEW #7** - Bob Corell Kearsarge Room
Image Processing	....
	TECHNOLOGY REVIEW #8 - Vic Anderson Narraganset Room
Vehicle Dynamics	Doug Humphreys, Aeronautical Research Associates of Princeton
3:00 p.m. - 3:30 p.m.	REGISTRATION OF NEW ARRIVALS
3:30 p.m. - 3:45 p.m.	Introduction - Robert W. Corell
3:45 p.m. - 5:00 p.m.	**Symposium Speaker:**
Deep Ocean Applications	Vic Anderson Marine Physics Laboratory Scripps Inst. of Oceanography
5:00 p.m. - 6:00 p.m.	
Informal Discussions	Elliot Alumni Center (refreshments courtesy of Hydro Products, Inc.)
Dinner	Personal arrangements

Thursday, September 24, 1981 - Berkshire Room

SYMPOSIUM SUMMARY

8:30 a.m. - 10:00 a.m.	**Summary of Technology Review** Vic Anderson Bob Corell
10:00 a.m. - 10:30 a.m.	Coffee
10:30 a.m. - 11:30 a.m.	**Resource Speaker:**
Deep Water Search for the Titanic - Limitations of Tethered Vehicles, Advantages of Autonomous Systems	William Ryan, Dale Chaves Lamont Doherty Geological Observatory of Columbia
11:30 a.m. - 1:00 p.m.	Lunch - personal arrangements
1:00 p.m. - 2:30 p.m.	
Inspection Mission	John Gregory U.S. Geological Survey
Arctic Applications	John Brook, Bedford Institute of Oceanography
Under Ice Hydrography	Cdr Van Neild Defense Mapping Agency
Ocean Science	Ian Morris University of Maryland
2:30 p.m. - 3:00 p.m.	Summary - Robert W. Corell Closing Remarks - Gene Allmendinger

These proceedings were compiled by Frank Busby, of Busby Associates for the Marine Systems Engineering Laboratory, University of New Hampshire and were edited by Louise K. Eklund. They are published by the Marine Systems Engineering Laboratory, Marine Program Building, University of New Hampshire, Durham, NH 03824 as contribution series number UNH-SG-CP-174.